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SNOW ABLATION PROCESSES
IN SMALL FOREST OPENINGS

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Abstract

The purpose of this study was to examine snow ablation processes in small forest openings. The two basic processes, melt and evaporation, are dependent upon energy fluxes that are influenced by microclimatological conditions caused by the openings.

Ablation, melt and evaporation were determined by a water balance technique using snow pans on north and south exposures of circular openings zero, one, three and five tree heights (0H, 1H, 3H and 5H) in diameter. The openings were located approximately 110 km northwest of Calgary, Alberta. Meteorological parameters (net radiation, wind speed, air temperature and relative humidity) were regressed against snow pan melt and evaporation. The calculation of melt by an energy budget method was used to compare with snow pan estimates of melt.

Total melt on south exposures varied from 70% (0H) to 98% (5H) of total ablation, and on north exposures it varied from 70% (0H) to 88% (1H). Evaporation was the residual in both cases. Melt was strongly correlated to net radiation in all size/exposures. Evaporation had no strong correlation with any single meteorological parameter. Energy budget estimates of melt did not approximate snow pan melt. The budget over-estimated melt when air temperature was low, and under-estimated melt when air temperature was high.

The size of canopy openings can affect ablation processes through changes in the energy regimen.

Meteorological conditions governed the relative contribution of energy inputs (e.g. net radiation, sensible heat and latent heat) to ablation. The horizontal transfer of sensible and latent heat may be of greater importance than the vertical transfer. The potential for water management via energy regimen manipulation is substantial.

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Table of Contents
Chapter

Page

I. INTRODUCTION	1
A. Background Statement	1
B. Processes	2
C. Harvesting Patterns	7
II. HYPOTHESES	10
III. METHODS	11
A. Study Area	11
B. Study Design	12
C. Instrumentation	12
Water Balance	12
Energy Budget	15
D. Energy Budget Model - Application and Assumptions	19
E. Data Analysis	20
IV. RESULTS	24
A. Meteorological Conditions	24
B. Timing of Ablation	29
C. Apportioning of Ablation	35
D. Energy Budget Estimation	40
V. DISCUSSION	49
A. Timing of Ablation	49
B. Apportioning of Ablation	51
C. Energy Budget Estimation	53
D. Additional Considerations	55
VI. CONCLUSIONS	56
A. Timing of Ablation	56

B. Apportioning of Ablation	56
C. Energy Budget Estimation	57
D. Questions	57
E. Concluding Remarks	58
References and Bibliography	60
Appendices	66

List of Tables

TABLE	Page
1. Designation of Size/Exposure Combinations.....	20
2. Precipitation.....	28
3. Snowmelt in Forest Openings as Ratios to Uncut (OH) Forest.....	38
4. Summary of Statistical Analyses.....	39
5. Correlation of Energy Budget Melt with Snow Pan Melt.....	40
6. Regression of Daily Snow Pan Melt and Evaporation on Meteorological Parameters.....	47
7. Regression of Daily Evaporation on Vapour Pressure Deficits.....	48

List of Figures

FIGURE	Page
1. Location of Snow Pans and Meteorological Instruments in Openings.....	13
2. Average Daily Air Temperature	25
3. Average Daily Relative Humidity	25
4. Total Daily Net Radiation (South Exposure).....	26
5. Total Daily Net Radiation (North Exposure).....	26
6. Average Daily Wind Speed (South Exposure).....	27
7. Average Daily Wind Speed (North Exposure).....	27
8. Average Daily Ablation (South Exposure).....	30
9. Average Daily Ablation (North Exposure).....	30
10. Average Daily Melt (South Exposure).....	32
11. Average Daily Melt (North Exposure).....	32
12. Average Daily Evaporation (South Exposure).....	33
13. Average Daily Evaporation (North Exposure).....	33
14. Average Daily Ablation as a Percentage of Total Ablation (South Exposure).....	34
15. Average Daily Ablation as a Percentage of Total Ablation (North Exposure).....	34
16. Average Daily Melt as a Percentage of Total Ablation (South Exposure).....	36
17. Average Daily Melt as a Percentage of Total Ablation (North Exposure).....	36
18. Average Total Melt as a Percentage of Total Ablation (South Exposure).....	37
19. Average Total Evaporation as a Percentage of Total Ablation (North Exposure).....	37
20. Snow Pan Melt vs. Energy Budget Melt (All Sizes/Exposures Combined).....	41
21. Snow Pan Melt vs. Energy Budget Melt (0).....	42

22.	Snow Pan Melt vs. Energy Budget Melt (1S).....	43
23.	Snow Pan Melt vs. Energy Budget Melt (1N).....	43
24.	Snow Pan Melt vs. Energy Budget Melt (3S).....	44
25.	Snow Pan Melt vs. Energy Budget Melt (3N).....	44
26.	Snow Pan Melt vs. Energy Budget Melt (5S).....	45
27.	Snow Pan Melt vs. Energy Budget Melt (5N).....	45

List of Symbols

SWE	snow water equivalent (mm)
Sm	melt (mm)
Se	evaporation-sublimation (mm)
Qm	energy available for melt (ly/day)
Qn	net radiation (ly/day)
Qh	sensible heat (ly/day)
Qe	latent heat (ly/day)
Qv	advected heat (ly/day)
Qg	conducted heat from ground (ly/day)
Qs	internal heat (ly/day)
Ua	wind (km/day)
Ta	air temperature (°C)
Ts	snow surface temperature (°C)
Zo	roughness length (m)
p	atmospheric pressure (mb)
Ea	vapour pressure of air (mb)
Es	vapour pressure of surface (mb)
P	precipitation (cm)
Cw	specific heat of water (cal/g/°C)
ρ_w	density of water (g/cm ³)

I. INTRODUCTION

Three essential goals of watershed management are water yield, quality and regimen regulation, with all other goals being derivations of these. The achievement of sound managerial decisions depends upon the attainment of an information base that reflects the true nature of these goals. To date, the major method of gathering information has been to investigate the physical attributes associated with these goals.

The purpose of this study is to examine one of the attributes common to both yield and regimen, namely snow ablation. Ablation is defined as the disappearance of snow resulting from melt, evaporation and sublimation.

A. Background Statement

The importance of snow as a source of water yield from mountain areas has long been recognized (Miner and Trappe, 1957; Anderson et al., 1958; Gary, 1980). Many attempts have been made to determine how these water producing zones might be managed to improve yield and regimen (Hart and Lomas, 1979; Haupt, 1979a; Troendle and Leaf, 1981). In most instances, management proposals have been reduction of the forest canopy by a number of different harvesting patterns, ranging from long strips (Haupt, 1979a) to irregularly shaped patch cuts (Dietrich and Meiman, 1974). To identify the most effective harvesting pattern, two concerns are important:

- 1) the physical processes involved in the accumulation and ablation of snow; and
- 2) how these processes are affected by specific harvesting patterns.

B. Processes

A significant amount of research has been conducted to determine and to understand the processes involved in snow accumulation and snow ablation (Bergen and Swanson, 1964). Accumulation has been treated strictly as a function of solid precipitation and is assumed to follow many of the same principles governing distribution of the liquid phase. Ablation is a composite of intricate, complex processes that are often expressed in simplified terms to make their study possible. Two approaches frequently used in snow ablation studies are: 1) water balance; and 2) energy budget.

A water balance of a snow pack can be expressed as:

$$\text{Ablation} = \Delta \text{SWE} = S_m + S_e \quad (1)$$

where SWE is the snow water equivalent, S_m is melt and S_e is evaporation-sublimation. All the terms are expressed as a volume or depth of water. Any change in SWE (i.e. ablation) is the sum of S_m and S_e . Melt is usually the dominant ablation process, followed by evaporation and sublimation. This ordering is based on the physics of phase change, which involves not only the delivery of energy, but also the

timing of that delivery (Lee, 1978). With certain weather conditions, however, evaporation can be an important ablation process. This is especially true when the vapour pressure gradient between the snow surface and the air is positive and large (Golding, 1978; Lee, 1978).

Techniques developed in previous research to quantify water balances are numerous. Most of these techniques are concerned with determining only one of the terms. Snow tubes are used extensively to estimate total ablation, but not its components of S_m and S_e (Golding and Swanson, 1978; Haupt, 1979a; Gary and Troendle, 1982). Schultz (1973) devised a lysimeter to measure melt, while West (1959, 1962) and Hutchison (1966) used snow pans to determine evaporation-sublimation. To study snow ablation by a water balance approach, both melt and evaporation-sublimation should be measured to ensure total ablation is accurately determined.

Snow pans can be designed to provide estimates of both melt and evaporation-sublimation. Early researchers such as West (1959, 1962) estimated snow evaporation only by measuring weight change over time of snow filled pans that allowed drainage of melt water. Retention and measurement of melt water, as done by Martinelli (1960b), provides a way of partitioning ablation into melt and evaporation-sublimation. Martinelli (1960b) used perforated false bottoms in the snow pans that allowed melt water to be collected and subsequently measured.

This technique has, however, inherent problems. The two most notable are:

- 1) the physical conditions (e.g. thermal regimen) within a pan are artificial and are not identical to those that exist surrounding the pan; and
- 2) the placement of snow into a pan disrupts the structure of the snow.

The first problem is a result of the material from which a pan is made. The material must have thermal properties similar to those of snow. Otherwise, the snow within a pan will be thermally isolated from the rest of the snow pack and subjected to different ablation conditions. Beck (1970) states that polyethylene plastic has a thermal conductivity of approximately $0.09 \text{ cal/cm/min/}^{\circ}\text{C}$ and a specific heat of $0.45 \text{ cal/g/}^{\circ}\text{C}$. These values compare well with those of snow, which are $0.13 \text{ cal/cm/min/}^{\circ}\text{C}$ and $0.50 \text{ cal/g/}^{\circ}\text{C}$, respectively (Lee, 1978). West (1959), in comparing metal and plastic pans, found that evaporation rates were not affected, but that snow melted much faster in the metal pans. Schultz (1973) was concerned that the plastic barriers used in his lysimeters would impede lateral heat transfer, intercept shortwave radiation and absorb sensible heat, all conditions which would affect ablation by changing the thermal regimen. He found that snow temperatures within and next to the lysimeters differed only slightly, usually only 0.5°C . He concluded that the plastic did not cause adverse effects.

The second problem is concerned primarily with the density of the snow. If the density is increased significantly by packing snow into pans, heat properties (e.g. thermal conductivity) will be increased due to decreased air space (Langham, 1981). This could result in more melt occurring within the pan than in the surrounding snow pack.

Since melt and evaporation-sublimation occur at the snow surface, the shape of that surface becomes important. West (1959) found that shovelling snow into a pan and smoothing the surface was similar to using an undisturbed snow core (about a 3% difference in evaporation), but differed greatly from an unsmoothed surface, which had nearly 40% more evaporation. The use of polyethylene plastic pans, and care in placing snow into the pans, can minimize these problems.

An energy budget to estimate ablation is conceptually simple. The total energy available for causing ablation, whether by melt and/or evaporation-sublimation, is the sum of the energy inputs minus the sum of the energy outputs (Anderson, 1968; Weisman, 1977). Most budgets have been developed to estimate only melt. Gray and O'Neill (1974) suggested that melt can be expressed as:

$$Q_m = Q_n + Q_h + Q_e + Q_v + Q_g - Q_s \quad (2)$$

where Q_m is the energy available for melt, Q_n is the net

radiation supplied to the snowpack, Q_h is the gain of energy by turbulent transfer of sensible heat from the air to the snow surface, Q_e is the gain of energy by turbulent transfer of latent heat (evaporation-condensation or sublimation) from the air to the snow surface, Q_v is the gain of energy by all vertical advective processes (e.g. rain), Q_g is the supply of energy to the snow pack by conduction from the underlying ground and Q_s is the increase in internal energy storage within the snow pack. These components are fluxes, and as such can be either positive (flow of energy towards the snow pack) or negative (flow of energy away from the snow pack) (Lee, 1978). The final component, Q_s , is assumed to be negligible when a melting snow pack is isothermal at 0°C (U.S. Corps. of Engineers, 1956).

The components of the budget are not equal in their contribution to the total energy available for melt. Dewalle and Meiman (1971) found that 54 to 64% of the energy supply came from net radiation, 41 to 49% from sensible heat transfer and that 3 to 5% was lost to evaporation. Müller and Keeler (1969) found that net radiation was followed in importance by sensible heat transfer. Similar results were obtained by Gold and Williams (1960), and Hendrie and Price (1978). Granger *et al.* (1977), in their study of the thermal regimen of a prairie snowcover, determined that net radiation flux was the major source of energy for melt, followed by sensible heat and latent heat. All these studies had independent measures of melt for comparison with

calculated values. In each case, good correlation was found between the calculated and measured melt.

The agreement among these different studies as to the order of contribution suggests that the theoretical background and practical techniques are sound, and can be applied with a fair certainty of success to other situations.

C. Harvesting Patterns

The effects of forest opening size, shape and orientation on snow accumulation have been studied extensively. There is a general agreement that the increased accumulation in openings is due in small part to decreased interception losses and in large part to a redistribution of the existing snow cover (Berndt, 1965; Dietrich and Meiman, 1974; Gary and Troendle, 1982).

Troendle and Leaf (1980, 1981), in their development of a hydrologic response model, considered the effects of forest openings on snowfall. They made the following conclusions: 1) With the dry snow of the Rocky Mountains, snowfall distribution on the ground is changed through the altering of the aerodynamic characteristics of the vegetative surface. In areas where snow is wet, redistribution by wind is less likely to occur. 2) Openings accumulate snow at the expense of the adjacent undisturbed forest, so that total basin snow storage is not changed (Gary, 1980; Hoover and Leaf, 1967). 3) Openings greater

than $15H$ in width (where H is the height of the surrounding trees) may cause decreased basin snow accumulation due to sublimation and mass movement of snow (wind scouring) out of the basin. 4) Optimum snow redistribution was assumed to occur when 50% or less of a basin is harvested in small openings less than $5H$ in diameter and spaced $5H$ to $8H$ apart.

These opening sizes are supported by Golding and Swanson (1978), who found that accumulation was greatest in openings of $2H$ to $3H$ in diameter, and then decreased with smaller and larger openings.

Individual snow ablation processes, as affected by harvesting patterns, have not been extensively investigated. In most studies, ablation has been regarded as a single process, with the major emphasis being on how fast or slow a snow pack disappears. Berndt (1965) determined that rates of snow disappearance were similar for cutblocks of 5, 10 and 20 acres, and that in all three cases rates exceeded those of the uncut forest. For an opening less than one acre, Gary (1974) found that rates were about twice those of the interior forest. Golding and Swanson (1978) studied ablation rates in small circular openings $1/4H$ to $6H$ in diameter (0.005 ac to 2.8 ac). Ablation rates were found to be lowest in openings $1H$ in diameter (0.08 ac) and higher not only in all other openings, but in the uncut forest as well. It was speculated that the higher rates in the forest and smaller openings were due to the greater amounts of longwave radiation emitted by the canopy. The higher rates in the

larger openings were due to greater amounts of advective energy from the air mass and solar radiation. The 1H opening was thought to be large enough that little longwave radiation reached the snow surface, and also small enough that very little solar radiation reached the surface.

In summary, ablation consists of two basic processes, melt and evaporation-sublimation. The relative proportion of each is dependent upon energy fluxes. These energy fluxes are, in turn, influenced by microclimatological conditions caused by the forest openings. Previous research has defined the general patterns of accumulation and ablation as influenced by forest openings of various shapes and sizes. However, how melt and evaporation-sublimation are affected by opening size alone has not been investigated.

II. HYPOTHESES

In order to harvest the forests in such a way as to manage the snow pack for streamflow, several questions must be considered. The major question in this study was: How are snow ablation processes affected by canopy opening size and direction of exposure within openings? In efforts to answer this question, three hypotheses were made:

- 1) Relative proportions of melt and evaporation-sublimation were not affected by opening size.
- 2) Relative proportions of melt and evaporation-sublimation were not affected by direction of exposure.
- 3) Snowmelt estimated by energy budget calculations was equal to melt estimated from snow pans.

III. METHODS

A. Study Area

The 15 km² study area was located 110 km northwest of Calgary, Alberta, between the Raven and James rivers. The cover was a uniform lodgepole pine (Pinus contorta Dougl. var. latifolia Engelm.) forest, with heights of 21-22 m, mean diameters at breast height of approximately 21 cm and a density of 1200 stems/ha. The site had a flat topography with sufficient fetch that wind patterns do not vary greatly over the whole area. The nearest significant topography change was 11 km to the southwest where the foothills of the Rocky Mountains began. Mean annual precipitation at Rocky Mountain House (40 km north) was 544 mm, of which 177 mm water equivalent fell as snow (using a 1:10 ratio of water equivalent to new snow) (Golding and Swanson, 1978).

Previous research into snow accumulation and ablation in forest openings was conducted in the area by Golding and Swanson (1978). They cut 72 circular openings, ranging in diameter from 1/4H to 6H, within a 2 km by 2 km grid. The openings were placed far enough apart that they did not affect each other. The openings were circular so that the width was the same for all wind directions. These conditions minimized any confounding factors caused by variations in forest cover and topography.

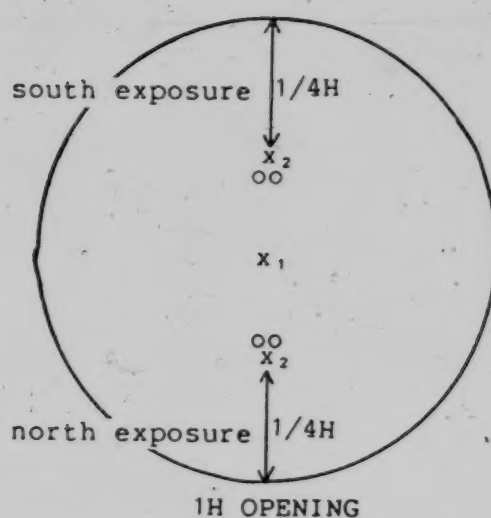
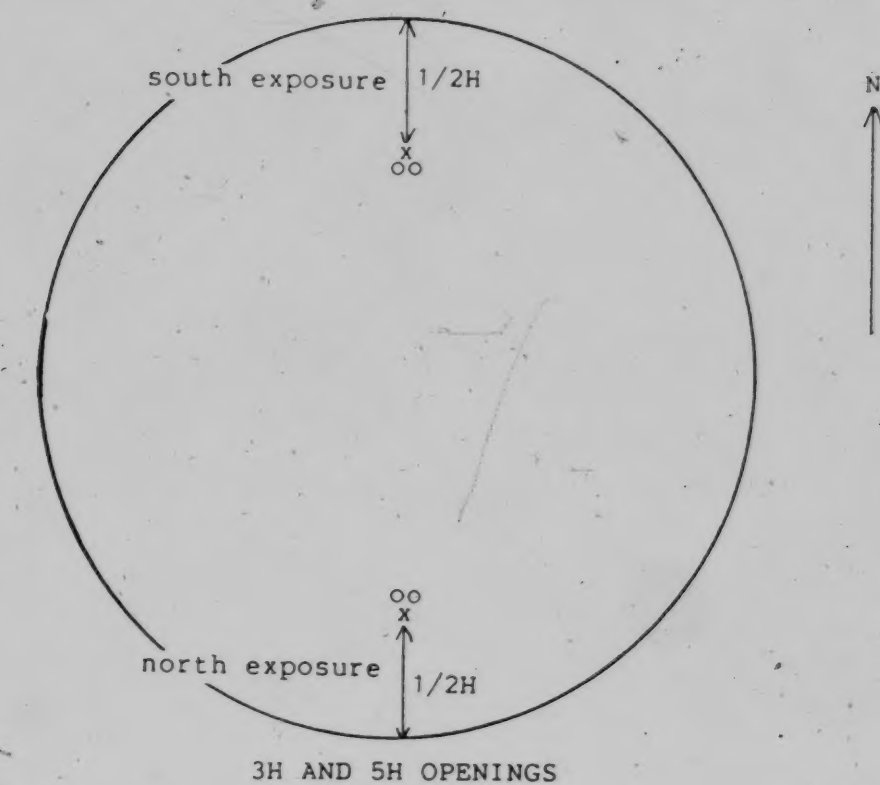
B. Study Design

Snow ablation processes were studied from April 2 to April 20, 1984, in two replications of circular forest openings of diameters 0H (uncut forest), 1H, 3H and 5H. These openings were selected based on Golding and Swanson's (1978) observations of a range of ablation rates in these sizes. Ablation, melt and evaporation-sublimation were determined by a water balance technique using snow pans. The calculation of melt by an energy budget method was used to compare with snow pan estimates of melt. It was assumed a high degree of correlation between water balance and energy budget estimates would imply that the energy budget gave a reasonable measure of melt. North and south exposures were sampled because they represented the apparent extremes in energy regimen within an opening.

C. Instrumentation

Water Balance

Snow ablation, melt and evaporation-sublimation were measured using snow pans. These pans consisted of circular, white polyethylene plastic containers (80 mm deep, 120 mm diameter) with perforated false bottoms to allow drainage of melt water for measurement. Two pans were placed at the north and south exposures $1/2H$ distance from the tree edge in the 3H and 5H openings, and $1/4H$ distance from the edge in the 1H openings (for a total of 24 pans)(Figure 1).



oo SNOW PANS

METEOROLOGICAL
INSTRUMENTS

x all instruments

x_1 anemometer/
thermistor

x_2 net radiometer/
relative humidity
and air temperature
probe

FIGURE 1. LOCATION OF SNOW PANS AND
METEOROLOGICAL INSTRUMENTS
IN OPENINGS

These distances were chosen because they corresponded to the location of the meteorological instrument towers. The towers were located and installed by Canadian Forestry Service scientists to meet specific objectives in their studies. North and south exposures of the uncut forest (OH) were assumed to be the same, so only four pans were placed in pairs at random within the uncut forest. This gave a total of 28 pans. Sampling was done twice per day, in the early morning (before 0900 hrs.) and early evening (after 1600 hrs.). Sampling in the evening prevented overnight freezing of drained melt water. If the melt water were allowed to freeze, it could affect ablation the next day by not allowing the snow sample to heat as quickly as the surrounding pack, thereby decreasing the amount of melt. Measurements were continued daily until ablation was complete.

Ablation, melt and evaporation-sublimation were determined by a series of weighings. At time t_0 , a pan (full of snow and no melt) was weighed (w_0). At t_1 , the pan was reweighed (w_1) and the difference in weights ($w_0 - w_1$) was assumed to be evaporation-sublimation for the intervening time. The melt was then drained from the false bottom and the pan reweighed (w_2). The difference ($w_1 - w_2$) was melt. Ablation was the total difference ($w_0 - w_2$). The calculation of these components is presented in Appendix 1 (p. 67).

Pans were refilled after each series of weighings by spooning snow in and smoothing the surface. The snow in this

study was not subject to heavy crystallization or ice layering, two conditions which would have made the spooning technique impractical due to changes in the internal structure and subsequent changes in ablation.

Once full and reweighed, the pans were inserted into the snowpack, making sure there were no gaps around the edges and that the pan surfaces were flush with the snow surface.

Evaporation and sublimation could not be separated with snow pans. Therefore, the term evaporation was assumed to include both factors.

Precipitation was measured by a single standard Meteorological Service of Canada 3.5-inch rain gauge placed at the centre of a 5H opening. Daily precipitation measurements were used as a basis for correcting snow pan estimates on days of precipitation.

Energy Budget

Snow melt in each opening was also estimated by an energy budget calculation using the Price and Dunne (1976) model:

$$Q_m = Q_n + Q_h + Q_e + Q_v \quad (3)$$

where Q_n , net radiation (ly/day), was obtained directly from net radiometer readings.

Q_h , sensible heat (ly/day), was calculated by:

$$Q_h = \frac{3.84 U_a (T_a - T_s)}{[\ln (Z_a/Z_o)]^2} \quad (4)$$

where U_a was total wind (km/day) at height Z_a (m) above the snow surface, T_a was air temperature ($^{\circ}\text{C}$) at height Z_a , T_s was snow surface temperature ($^{\circ}\text{C}$) and Z_o was the roughness length (m). This last factor was the most difficult to estimate, but for snow surfaces, Dunne and Leopold (1978) suggested a value of 0.005 m be used.

Q_e , latent heat (ly/day), was calculated by:

$$Q_e = \frac{7592 U_a (E_a - E_s)}{p[\ln (Z_a/Z_o)]^2} \quad (5)$$

where p was atmospheric pressure (mb), E_a was vapour pressure of the air (mb) at height Z_a and E_s was vapour pressure of the surface (mb).

When T_a was greater than T_s (i.e. stable air conditions) (Sverdrup, 1936; Anderson, 1976), the turbulent exchange of energy was decreased at the snow surface and so Q_h and Q_e needed to be reduced. Equations 4 and 5 were therefore divided by K , a stability reduction factor derived from Richardson's number, where:

$$K = 1 + \frac{732310 Z_a (T_a - T_s)}{(T_a + 273) U_a^2} \quad (6)$$

Q_v , advected heat (ly/day) from rain, was calculated by:

$$Q_v = P T_a C_w \rho_w \quad (7)$$

where P was rainfall (cm), C_w was the specific heat of water (1.0 cal/g/°C) and ρ_w was the density of water (1.0 g/cm³).

Snowmelt was determined by:

$$M = \frac{Q_m}{80 \rho_w} \quad (8)$$

where M was the melt rate (cm/day), 80 cal/gm was the latent heat of fusion of ice and ρ_w was the density of water (1.0 g/cm³).

The derivation of these equations is given by Price and Dunne (1976). The constants in Equations 4, 5 and 6 are to account for such factors as air density, specific heat of air, latent heat of vaporization, exchange coefficients for heat and moisture and unit conversion.

Energy budget components were calculated from meteorological observations obtained in the openings.

One 3H and one 5H opening were each instrumented with:

- 1) two Fritschen (Fritschen, 1963) net radiometers,
- 2) two RH/air temperature probes (similar to Campbell Scientific Model 201 RH sensor),
- 3) two 3-cup anemometers, and

- 4) two thermistors.

One of each instrument was placed at the north and south exposures $1/2H$ in from the tree edge (Figure 1).

One $1H$ opening was instrumented with:

- 1) two CSIRO (Funk, 1959) net radiometers,
- 2) two RH/air temperature probes,
- 3) one 3-cup anemometer, and
- 4) one thermistor.

One net radiometer and one RH/air temperature probe were located in the north and south exposures $1/4H$ in from the tree edge. The anemometer and thermistor were placed in the centre of the opening (Figure 1).

The $0H$ opening had one net radiometer, one RH/air temperature probe, one anemometer and one thermistor.

All net radiometers, RH/air temperature probes and anemometers were mounted two metres above the snow pack and the thermistors were placed at a depth of 2-3 cm below the snow surface. The stall speed of the anemometers was estimated to be less than 1.0 m/s (Wang and Felton, 1979).

The locations of the instruments within the openings coincided with the locations of the snow pans.

Data output from the instruments was monitored with Campbell Scientific CR21 data loggers, programmed to take one-minute spot readings which were then averaged for a 15 minute period. These 15-minute averages were used to determine daily averages.

Precipitation was measured by a single nonrecording rain gauge at the centre of a 5H opening.

D. Energy Budget Model - Application and Assumptions

There were a number of advantages and disadvantages in using the Price and Dunne (1976) model. The two most notable advantages were: 1) it is generally applicable to situations beyond the subarctic for which it was developed; and 2) it considers the effects of conditions over the snow surface (e.g. surface versus air temperature, surface roughness) on turbulent exchanges of energy between the air and snow (Price and Dunne, 1976). The major disadvantage was that no consideration was given to the energy transfer processes that occur within the snow pack. The snow pack was treated as a one dimensional system, with the budget components acting as inputs and outputs.

The following assumptions were made by Price and Dunne (1976) in the application of the model to account for these considerations:

- 1) The system was one-dimensional (i.e. no lateral transfer of energy) (Weisman, 1977).
- 2) The snowpack was isothermal at 0°C during melt (Anderson, 1968).
- 3) E_s in the calculation of Q_e was equal to saturation vapour pressure at 0°C (Anderson, 1968).
- 4) Energy transfer from the ground (Q_g) was

negligible (Male and Gray, 1981).

E. Data Analysis

Seven different size/exposure combinations were defined by size of opening and exposure. Each combination was designated as in Table 1.

TABLE 1. DESIGNATION OF SIZE/EXPOSURE COMBINATIONS

Exposure	Opening Size			
	0H	1H	3H	5H
North	0	1N	3N	5N
South	0	1S	3S	5S

e.g. 1H opening, north exposure = 1N

The following parameters were plotted against time for each size/exposure combination:

- 1) average daily air temperature, °C
- 2) average daily relative humidity, %
- 3) total daily net radiation, ly/day
- 4) average daily wind speed, m/s
- 5) average daily ablation, mm H₂O
- 6) average daily melt, mm H₂O
- 7) average daily evaporation, mm H₂O
- 8) average daily ablation as a percentage of total ablation
- 9) average daily melt as a percentage of total ablation

The following plots were also generated:

- 1) average total melt as a percentage of total ablation
- 2) average total evaporation as a percentage of total ablation
- 3) snow pan melt (mm/day) vs. energy budget melt (mm/day)

The snow pan data for total melt and total evaporation as percentages of total ablation for all size/exposure combinations underwent three statistical analyses.

Percentages were used for two reasons: 1) all measurement locations did not initially have equal amounts of snow; and 2) total snow pack ablation did not occur at the same time at all locations.

Before the analyses were performed, the percentage data were subjected to the following tests:

- 1) D'Agastino's test of normality (Zar, 1974); and
- 2) Bartlett's test for homogeneity of variances (Steel and Torrie, 1980).

The data satisfied these tests, and therefore the subsequent analyses were valid. A split plot analysis of variance (Steel and Torrie, 1980) was conducted to determine which was the greater source of variation in the data, size or exposure. A multiple comparison of means using Duncan's Multiple-Range test (Steel and Torrie, 1980) was done to detect differences between sizes with the same exposure (e.g. 0 1N 3N 5N). T-tests were used to detect differences between exposures in the same opening (e.g. 1N vs. 1S).

Because the melt and evaporation data were proportions of the same total, any differences in one meant reciprocal differences in the other. Accordingly, analysis of both sets of data would give identical statistical results. Therefore only the melt data were analysed.

These three analyses were required due to the restrictions of a split plot design. There were interactions between size and exposure that could not be separated. It may be possible to detect a difference between (e.g.) 5N and 1S, but it would not be possible to identify whether this difference was caused by size or exposure (R.T. Hardin. pers. comm. Dept. Animal Sci., U. Alberta, 1985).

Snow pan melt estimates were regressed against energy budget melt estimates and the resulting correlation coefficients (r) and standard errors (Se) were examined. Multiple linear regressions of meteorological parameters versus daily melt and evaporation were performed to see if ablation processes could be explained in terms of meteorological data. Daily evaporation was also regressed against:

- 1) vapour pressure deficit (assuming snow surface temperature was 0°C),
- 2) vapour pressure deficit (assuming snow surface temperature was 0°C) and average wind speed, and
- 3) vapour pressure deficit (assuming snow surface temperature was equal to snow temperature 2-3 cm below the surface) and average wind speed.

Care was taken to ensure that the daily meteorological measurements covered the same time period as the daily melt/evaporation measurements.

IV. RESULTS

A. Meteorological Conditions

Over the 17 days of measurement, a variety of meteorological conditions were sampled (Figures 2 to 7, p. 25-27). Maximum and minimum values of meteorological parameters are given in Appendix 2 (p. 68). Weather varied from cool, cloudy and dry (April 12), to warm, cloudy and moist (April 18), to hot, clear and dry (April 16). Average daily air temperatures were similar for all size/exposures, showing a variable but increasing trend. Values ranged from minima of -0.3°C to 3.4°C for April 3-12, to maxima of 6.1°C to 12.9°C for April 14-16. These higher temperatures were caused by the movement of a warm air mass into the area. Relative humidity, because of its temperature dependence, showed a pattern similar to air temperatures, but reversed. Average daily relative humidity varied from 37% to 100%, with two maximum peaks of 86% and 100%, which coincided with the days of greatest precipitation. Generally, conditions were fairly moist, with most days having a relative humidity greater than 50%.

Total precipitation during the 17 days was 15 mm (Table 2, p. 28). Precipitation occurred in two storms, one on April 6-7 of 5 mm, and the other on April 18-20 of 10 mm. For both storms, precipitation was principally rainfall.

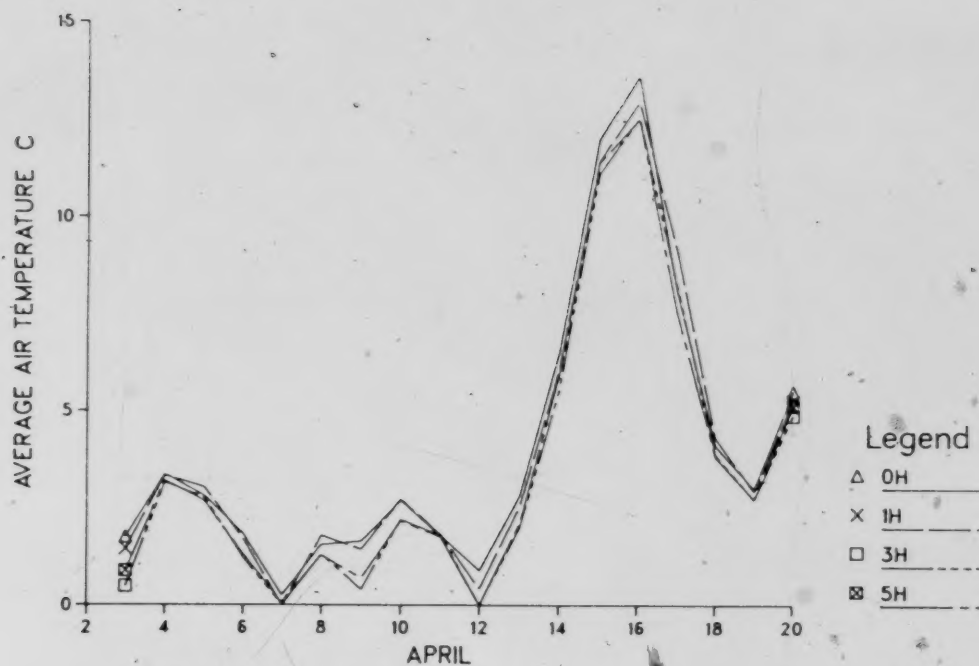


FIGURE 2. AVERAGE DAILY AIR TEMPERATURE

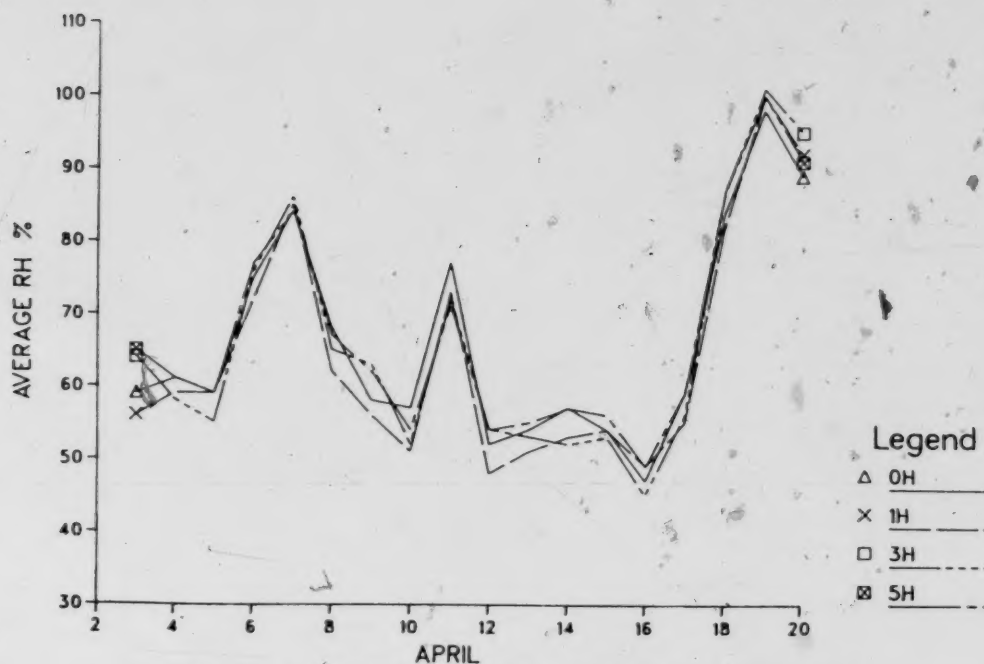


FIGURE 3. AVERAGE DAILY RELATIVE HUMIDITY

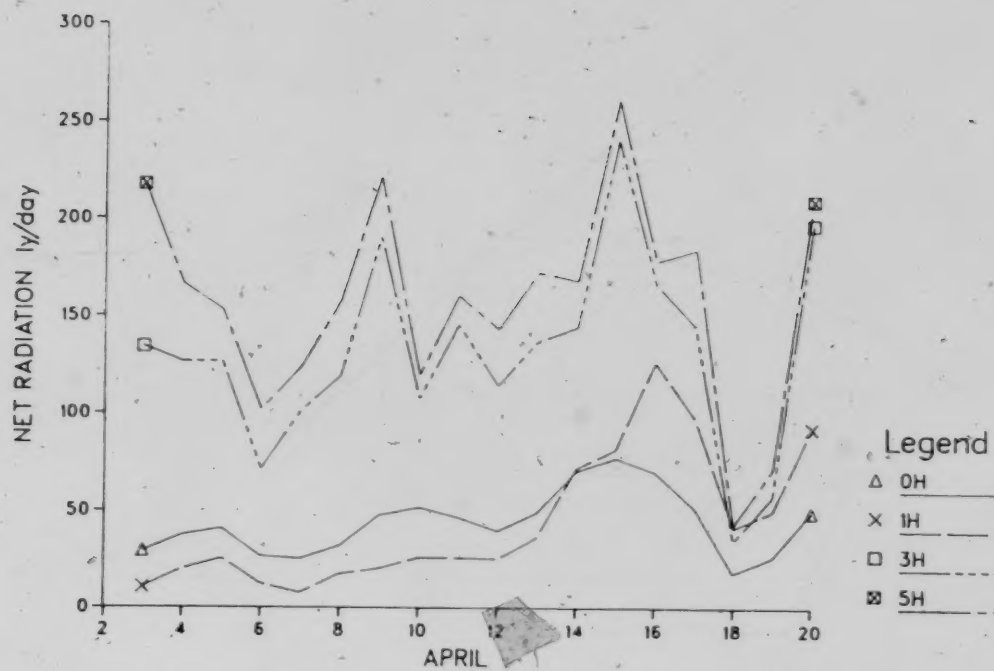


FIGURE 4. TOTAL DAILY NET RADIATION
(SOUTH EXPOSURE)

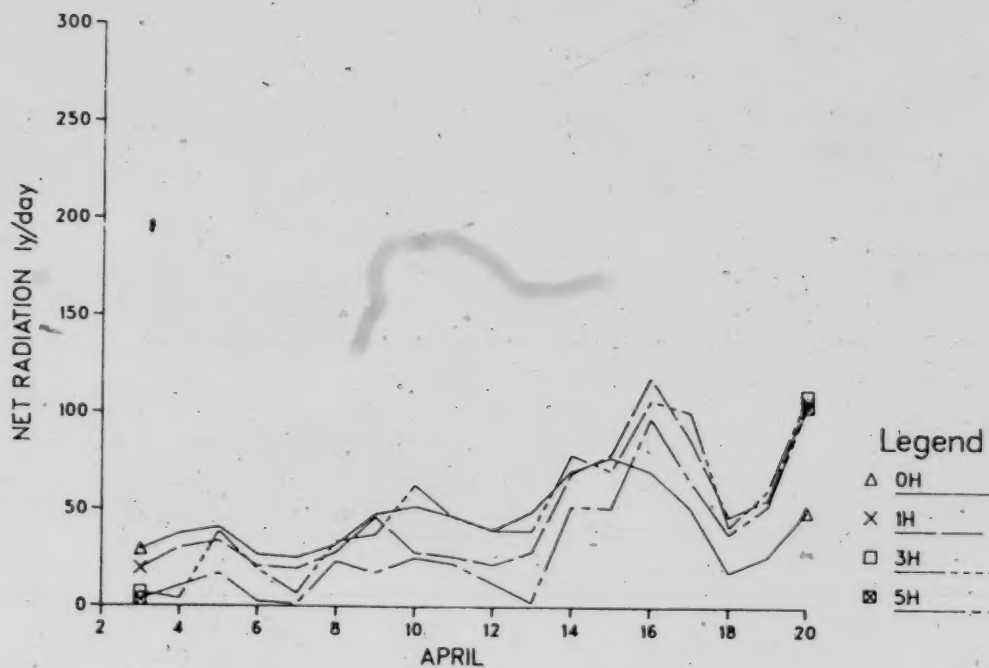


FIGURE 5. TOTAL DAILY NET RADIATION
(NORTH EXPOSURE)

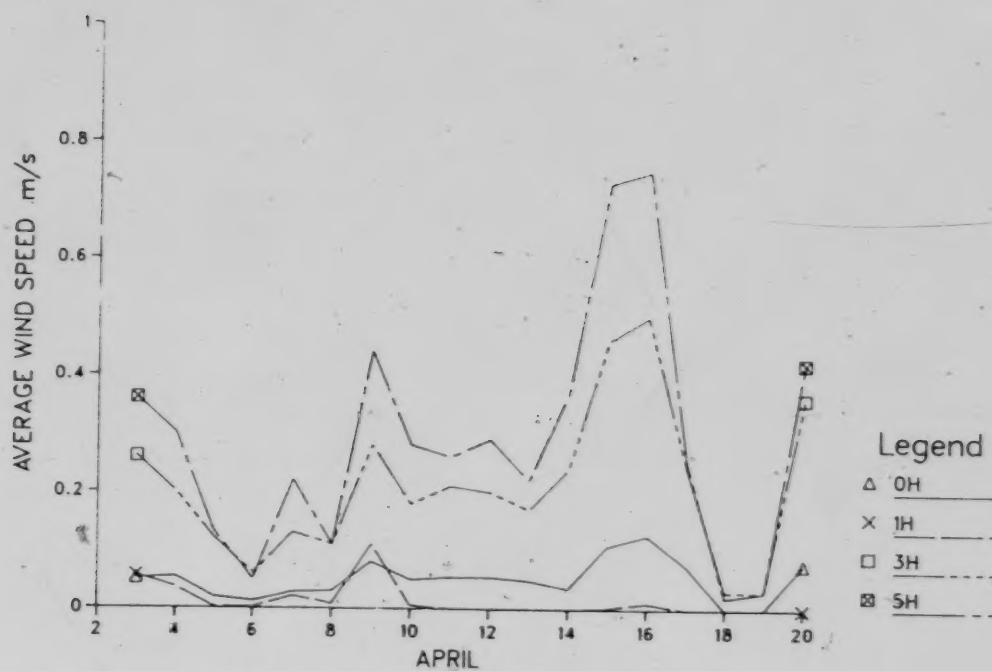


FIGURE 6. AVERAGE DAILY WIND SPEED
(SOUTH EXPOSURE)

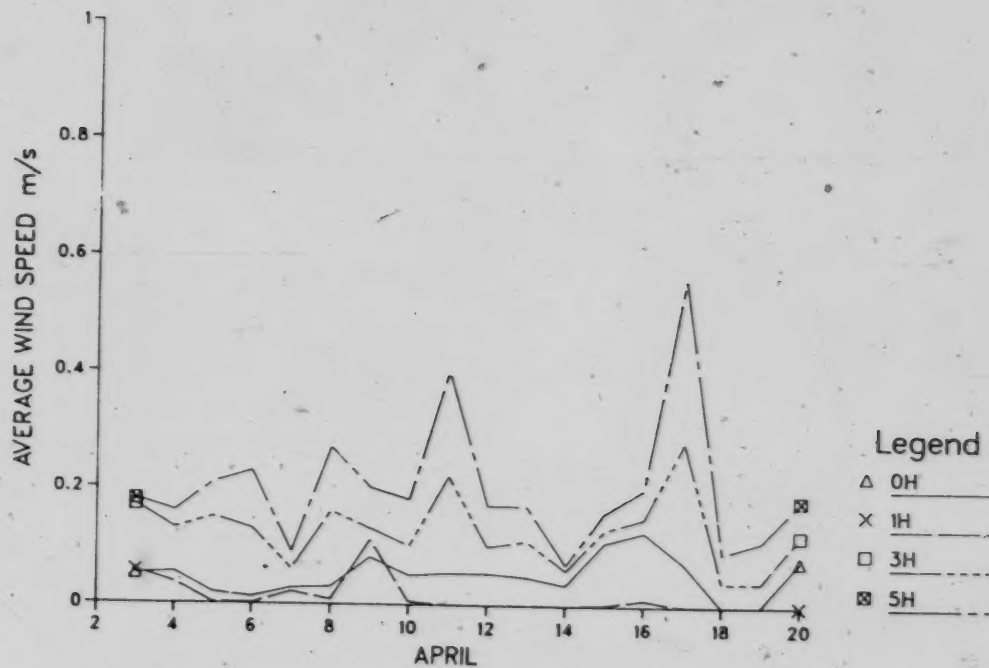


FIGURE 7. AVERAGE DAILY WIND SPEED
(NORTH EXPOSURE)

TABLE 2. PRECIPITATION (mm)

April	6	1
	7	4
	18	3
	19	5
	20	2

Total .15

Net radiation varied greatly between size/exposures. Total daily net radiation was greatest on south exposures, especially in the 3H and 5H openings, with values ranging from 37 ly/day to 262 ly/day. The other size/exposures received considerably less net radiation, only 1 ly/day to 126 ly/day. On average, 3S and 5S received three times more net radiation than the other size/exposures. Zero and 1S had both similar trends and similar magnitudes to the north exposures, which were all alike, starting with low values that gradually increased to higher levels. Both 1S and 1N were consistently less than 0 until April 14, when a cross-over occurred and 0 decreased while the other two increased.

Wind speed also varied considerably between opening sizes. As might be expected, wind speed increased with opening size, with average wind speed in the 3H and 5H openings almost seven times greater than in the 0H and 1H openings. Minimum wind speed occurred in the 1H rather than in the 0H opening. No trends were apparent between wind speed and exposure.

B. Timing of Ablation

On the first day of measurement (April 2) the approximate snow depths were: 3S and 5S, 30 cm; 0, 50 cm; 1S and 1N, 60 cm; 3N and 5N, 80 cm. Measurements were continued until there was roughly 50% snow cover around the instrument towers. Snow pack disappearance (to 50% coverage) occurred on different days for each size/exposure combination. The order of disappearance was: 3S and 5S (April 9); 0 (April 14); 1S (April 19); 1N, 3N and 5N (April 21). There was still some snow present on the north exposures after the last day of measurement (April 20), but it was not near enough to the instrument towers for measurements to be taken.

The trends in daily ablation rates displayed by each size for both north and south exposures were similar (Figures 8 and 9, p. 30). Ablation rates for all size/exposures, except 3S and 5S, were similar in magnitude (0.1 mm/day to 22.8 mm/day) and generally increased over time. The south exposures of the 3H and 5H openings had much greater ablation rates than the other size/exposures for corresponding days (8.2 mm/day to 20.2 mm/day versus 0.1 mm/day to 6.6 mm/day), but they did follow the same short-term increase - decrease - increase trend. These similarities would seem to indicate that the conditions governing ablation were similar for each opening size. Indeed, the large increase in ablation after April 14 suggests that there was a marked change in these conditions,

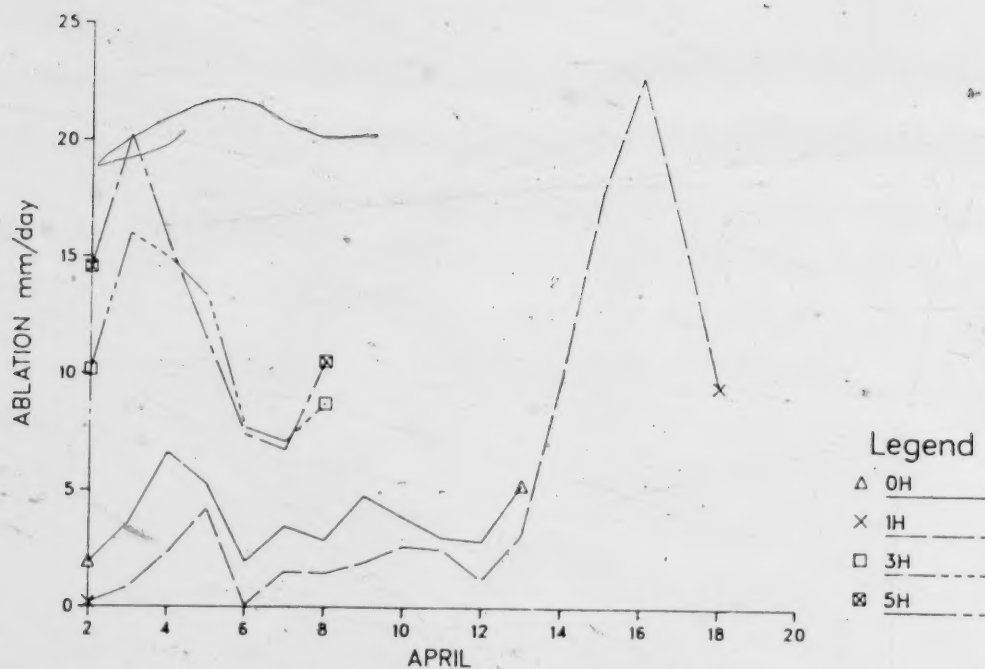


FIGURE 8. AVERAGE DAILY ABLATION
(SOUTH EXPOSURE)

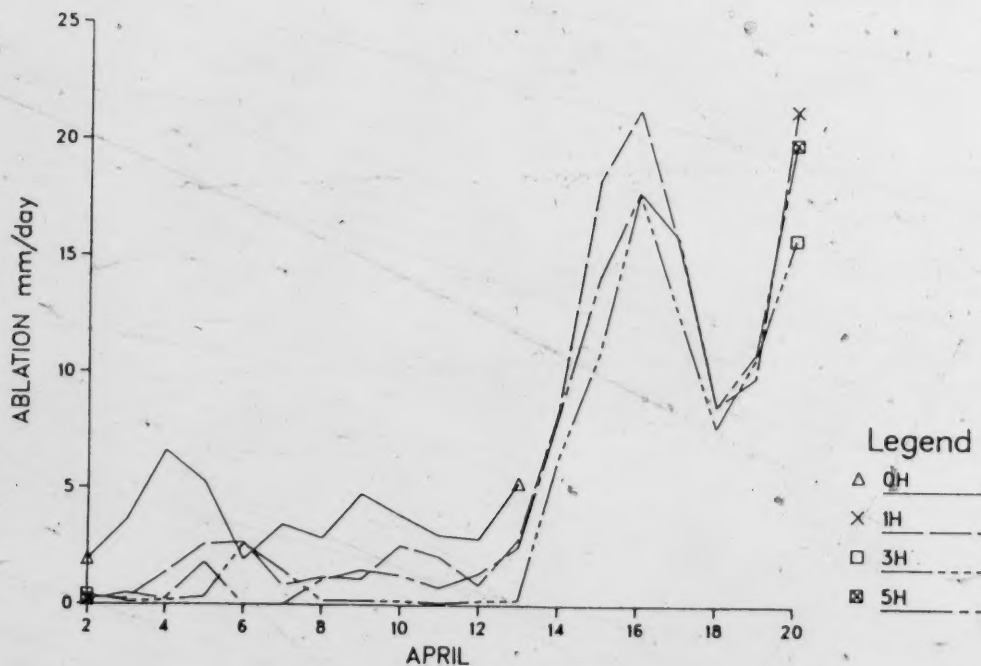


FIGURE 9. AVERAGE DAILY ABLATION
(NORTH EXPOSURE)

notably higher air temperatures and greater net radiation inputs. The 1H opening had the greatest amount of ablation for a single day on April 16, with values of 21.3 mm (north exposure) and 22.8 mm (south exposure).

Daily melt rates are presented in Figures 10 and 11 (p. 32). The similarity between these and Figures 8 and 9 illustrates the importance of melt as an ablation process. Melt values varied from 0.0 mm/day (0H) to 21.4 mm/day (1H) for south exposures and from 0.0 mm/day (1H, 3H, 5H) to 22.9 mm/day (1H) for north exposures.

Trends in daily evaporation values are presented in Figures 12 and 13 (p. 33). As with melt, evaporation also had similar trends for both exposures, with a general decrease in rates over time. Condensation (i.e. negative evaporation) occurred on three occasions (other than rain days), with the 1H opening experiencing the greatest amount from both exposures on April 11. Evaporation rates ranged from -2.2 mm/day to 1.3 mm/day, but these were extremes. Most of the values were between -0.4 mm/day and 0.4 mm/day. The few extreme values were omitted from the graphs because they exceeded the scale, but they were included in the statistical analyses. The extreme values occurred on days of precipitation. Generally, evaporation decreased as precipitation increased.

The distribution of ablation over time is illustrated in Figures 14 and 15 (p. 34). Snow disappeared from the south exposures first in 3H and 5H, then 0H and finally 1H.

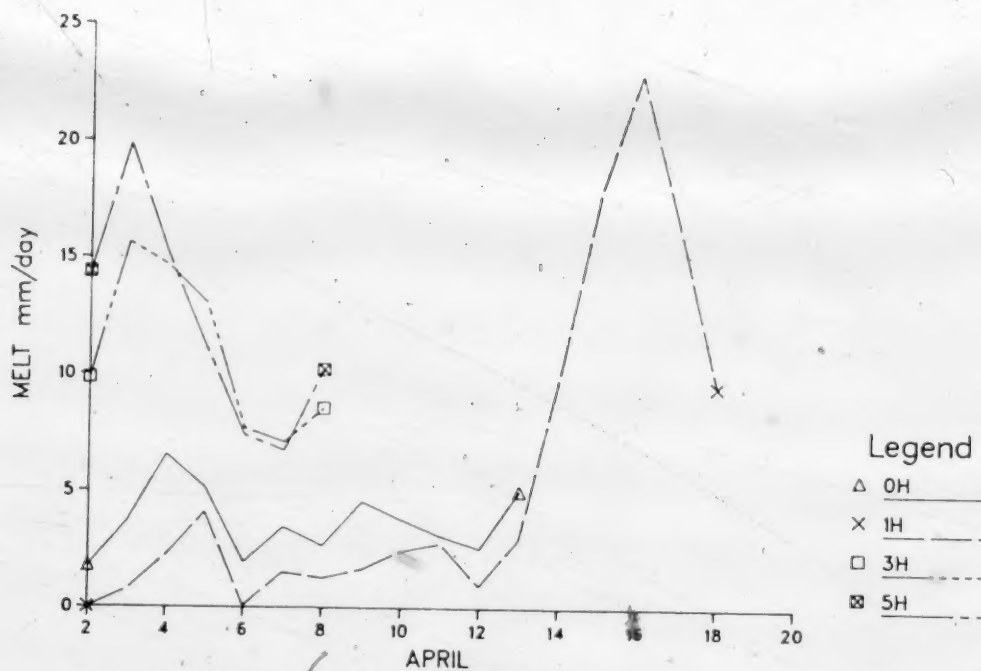


FIGURE 10. AVERAGE DAILY MELT
(SOUTH EXPOSURE)

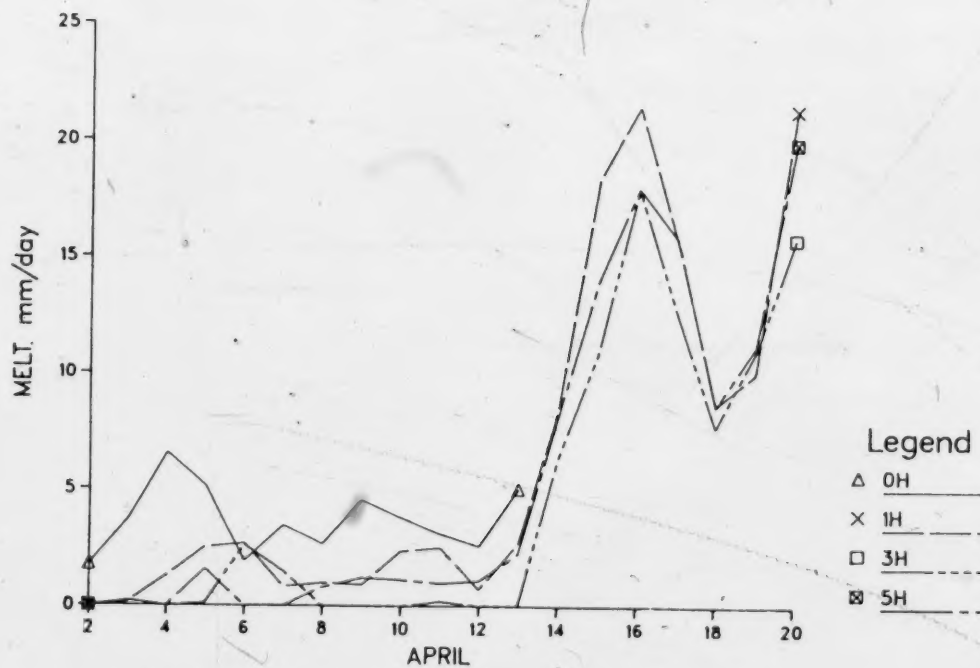


FIGURE 11. AVERAGE DAILY MELT
(NORTH EXPOSURE)

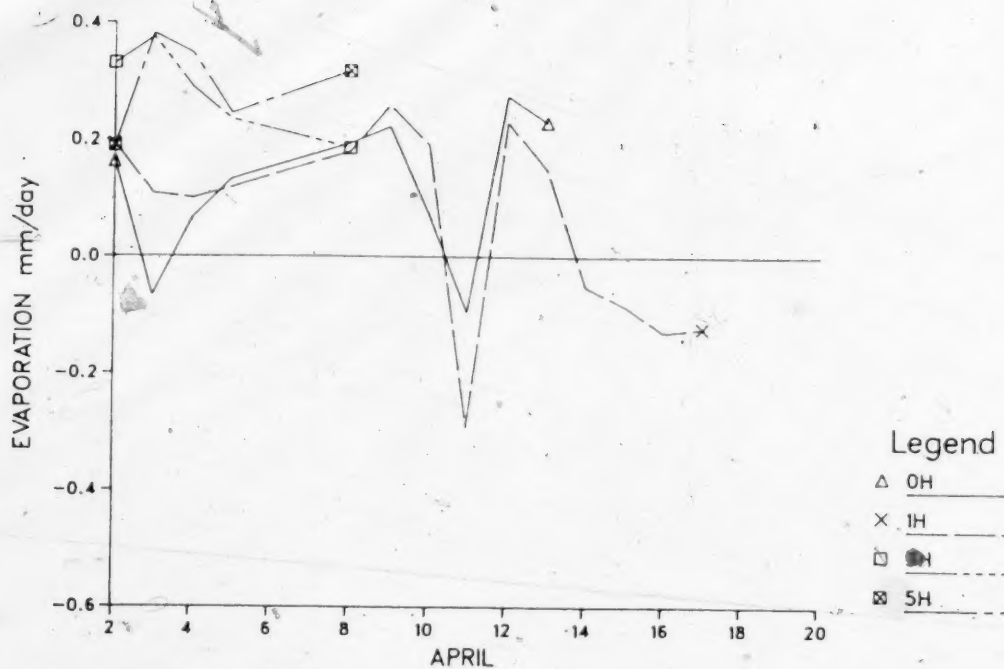


FIGURE 12. AVERAGE DAILY EVAPORATION
(SOUTH EXPOSURE)

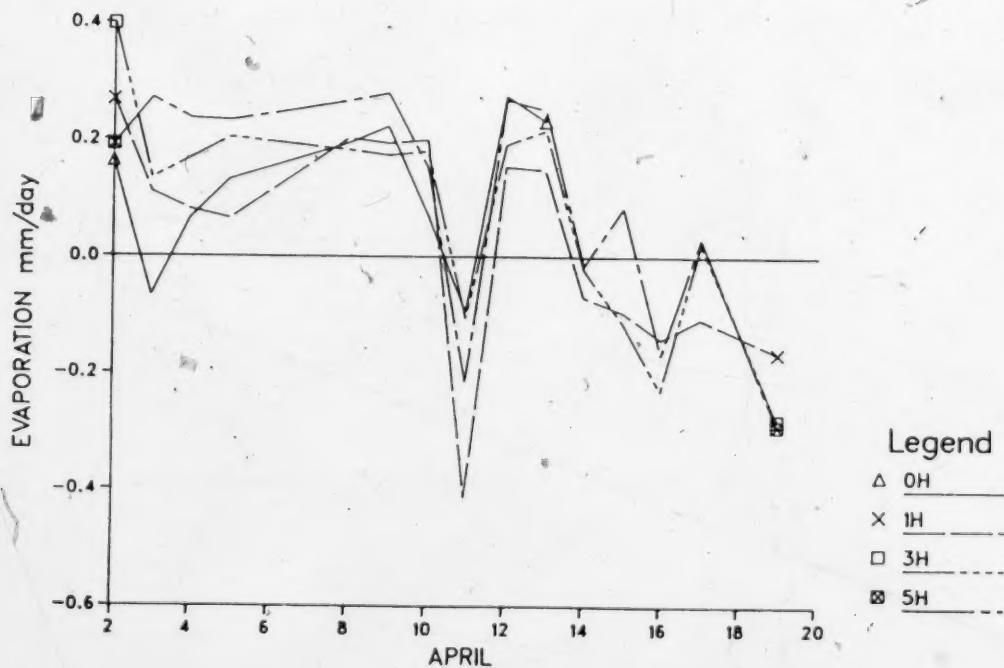


FIGURE 13. AVERAGE DAILY EVAPORATION
(NORTH EXPOSURE)

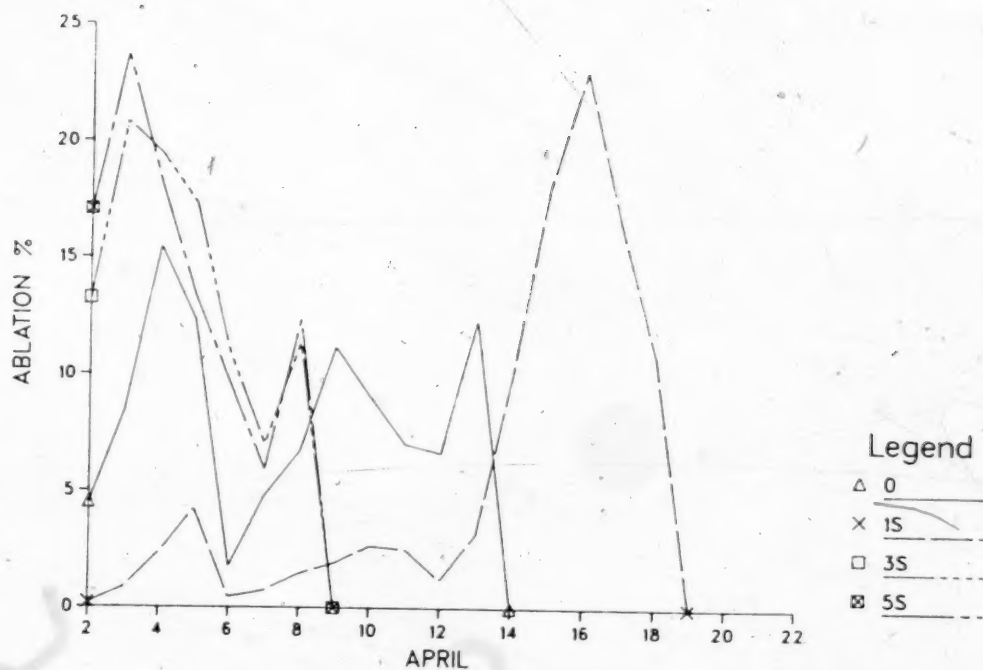


FIGURE 14. AVERAGE DAILY ABLATION AS A PERCENTAGE OF TOTAL ABLATION (SOUTH EXPOSURE)

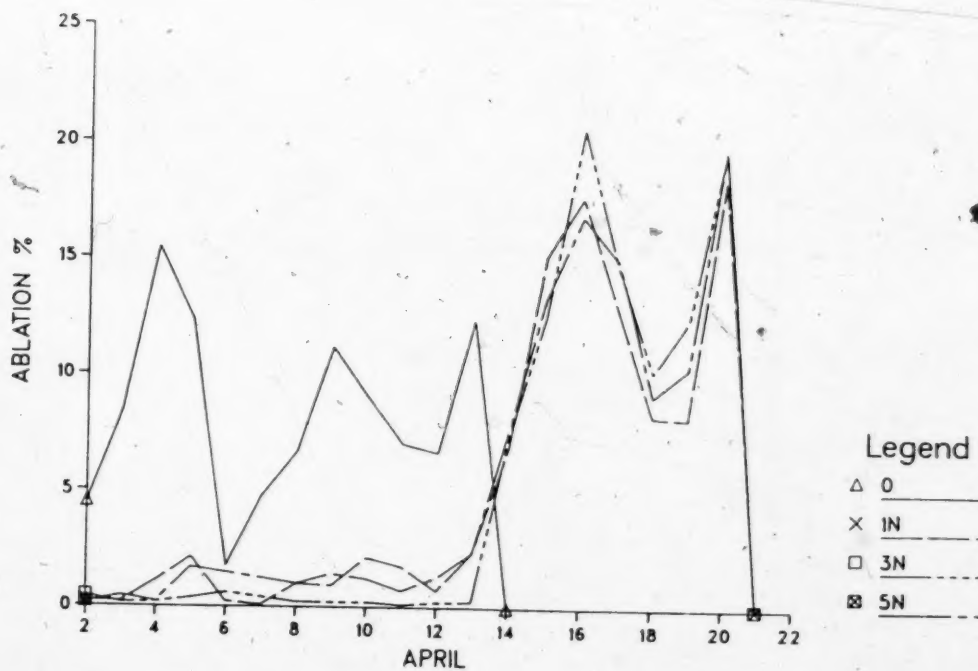


FIGURE 15. AVERAGE DAILY ABLATION AS A PERCENTAGE OF TOTAL ABLATION (NORTH EXPOSURE)

Almost all of the ablation in 1S occurred between April 12 - 19, after snow was gone from the other openings. The north exposures of 1H, 3H and 5H had very similar ablation patterns, with almost all of it occurring between April 14 - 21 and after 0H was clear of snow. Both 1S and 1N peaked on April 16, but 1N had an additional peak on April 20, when there was no more snow in 1S. No single day accounted for more than 25% of a size/exposure's total ablation.

The distribution of melt over time is shown in Figures 16 and 17 (p. 36). The patterns for both exposures are almost identical to those of ablation. The only real differences occurred for days of precipitation and condensation, when melt was greater than ablation.

C. Apportioning of Ablation

Although daily fluctuations are of interest, total evaporation and melt, and thereby the net input of water into the hydrologic system from the snow pack, are of more concern. These totals are represented in Figures 18 and 19 (p. 37). Melt was the dominant ablation process and accounted for 70% to 97% of total ablation on south exposures, and 70% to 89% on north exposures. Evaporation constituted the remainder (3% to 30%). The differences in melt between opening sizes are given in Table 3 (p. 38). Melt increased with opening size, ranging from 14% to 27% more melt than in the uncut forest, and evaporation decreased with opening size, especially on south exposures.

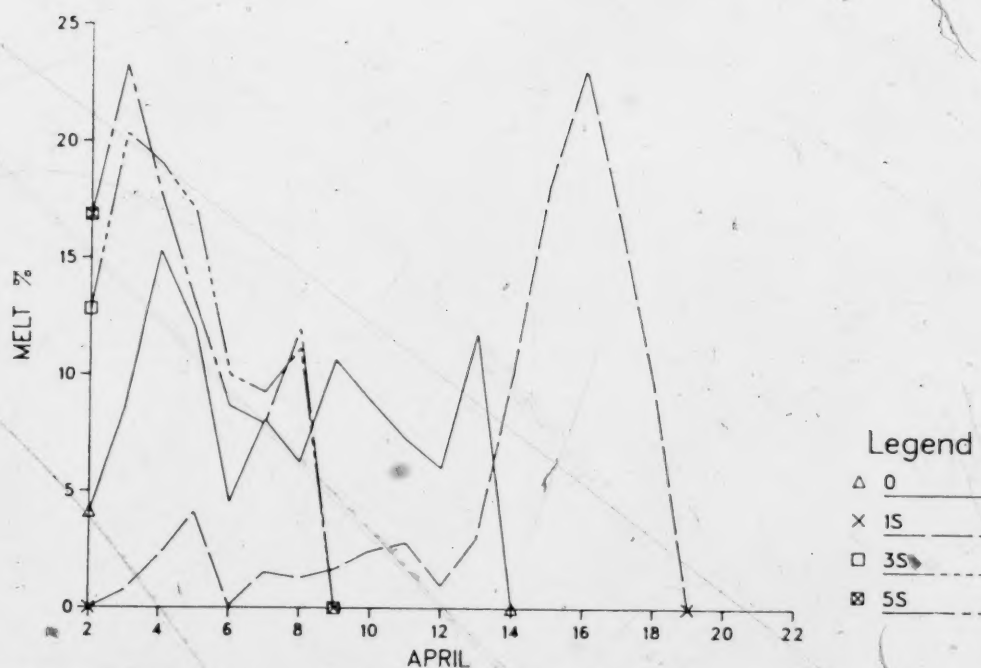


FIGURE 16. AVERAGE DAILY MELT AS A PERCENTAGE OF TOTAL ABLATION (SOUTH EXPOSURE)

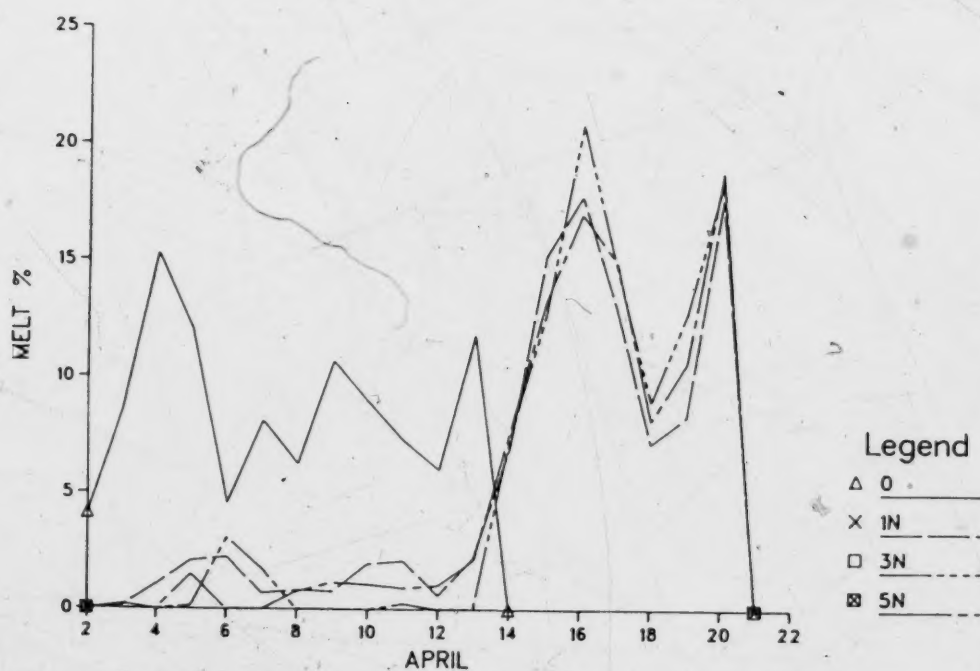


FIGURE 17. AVERAGE DAILY MELT AS A PERCENTAGE OF TOTAL ABLATION (NORTH EXPOSURE)

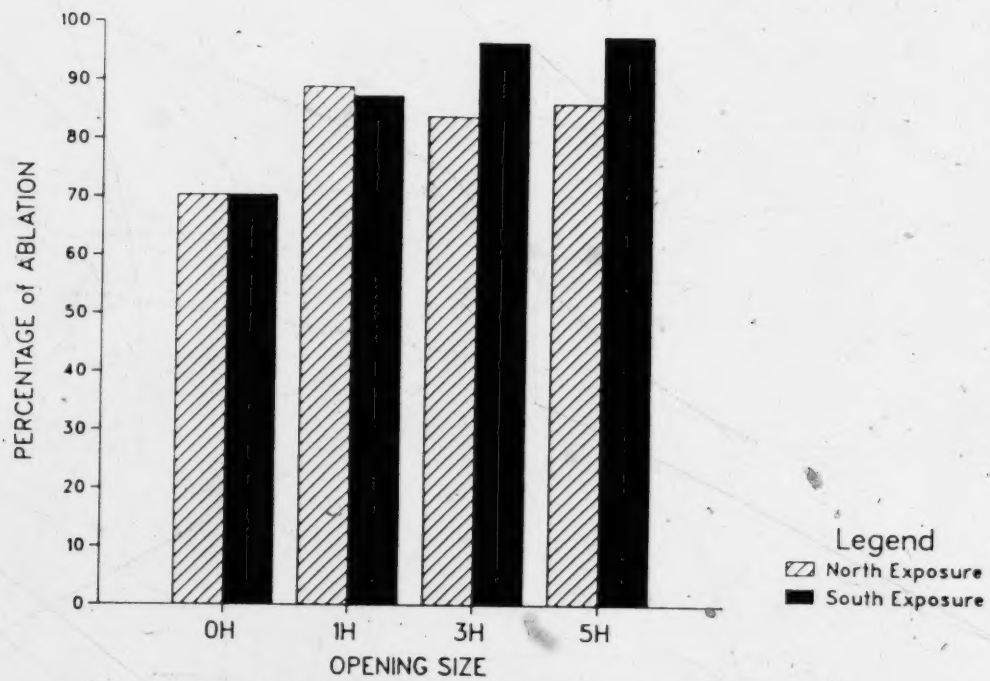


FIGURE 18. AVERAGE TOTAL MELT AS A PERCENTAGE OF TOTAL ABLATION

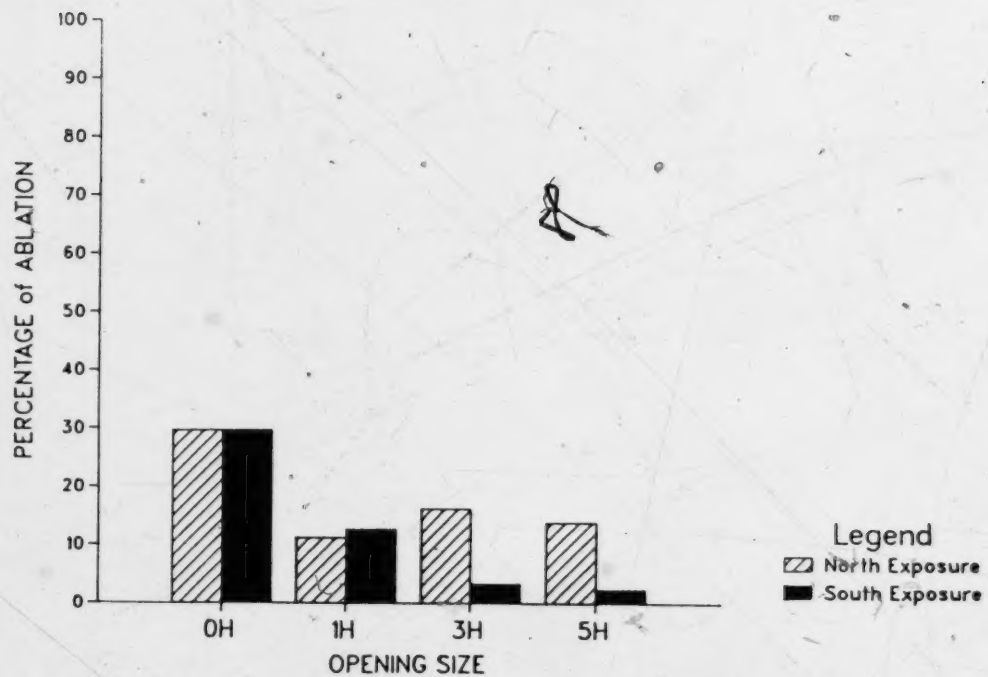


FIGURE 19. AVERAGE TOTAL EVAPORATION AS A PERCENTAGE OF TOTAL ABLATION

TABLE 3. SNOWMELT IN FOREST OPENINGS AS RATIOS TO UNCUT (0H) FOREST

Size	Exposure		Mean
	N	S	
0H	1.00	1.00	1.00
1H	1.19	1.17	1.18
3H	1.14	1.26	1.20
5H	1.16	1.27	1.22

The results of the three statistical analyses are summarized in Table 4 (p. 39). The ANOVA showed that the most significant differences in melt and evaporation were due to exposure, followed by exposure/size interaction and finally size. All three sources had significant F values, with the F value for exposure being almost five times greater than the F value for size.

The multiple comparison of means for detecting melt and evaporation differences between sizes showed that melt increased (and evaporation decreased) significantly with increasing opening size, but only to a certain point. The south exposures of the 3H and 5H openings did not differ, nor did the north exposures of the 1H, 3H and 5H openings.

The T-test results for detecting differences between exposures showed that there was more melt (less evaporation) on the south exposures than on the north exposures of the 3H and 5H openings. For the 1H opening, there was more melt (less evaporation) on the north exposures.

TABLE 4. SUMMARY of STATISTICAL ANALYSES

1) SIZE AND EXPOSURE ANOVA:

SOURCE	df	MS	F	
block	1	0.0030	0.50	
size	3	0.0800	13.57*	
error(a)	3	0.0058		main plot
exposure	1	0.0260	64.70**	
exp/size	3	0.0114	28.22**	
error(b)	4	0.0004		split plot
ERROR	16			
TOTAL	31			

* significant at 0.10 level

** significant at 0.05 level

2) SIZE COMPARISON: Duncan's Multiple Range Test

	S	N
0H	a	a
1H	b	b
3H	c	b
5H	c	b

Sizes with same letter not
significantly different
at 5% level.

3) EXPOSURE COMPARISON: t-tests

0H	---
1H	*
3H	*
5H	*

* exposures significantly different
at 5% level

D. Energy Budget Estimation

Estimates of energy budget melt and snow pan melt showed close agreement, but only if all the data were combined (Figure 20, p. 41). Snow pan melt varied from 0 to 22.9 mm/day, with a grand mean for all size/exposures of 6.3 mm/day. Energy budget melt varied from 0.1 to 27.1 mm/day, with a mean of 6.7 mm/day. Individual plots of size/exposure estimates (Figures 21 to 27, p. 42-45) showed that the energy budget tended to either over or under-estimate melt. The correlation coefficients were high, except for 0H, ranging from 0.88 to 0.99 (Table 5) and the standard errors were quite low (1.3 to 3.9 mm/day). Comparisons with the meteorological data revealed that the energy budget over-estimated melt (0, 3S, 5S) when air temperature was low, and under-estimated melt (1S, 1N, 3N, 5N) when air temperature was high.

TABLE 5. CORRELATION OF ENERGY BUDGET MELT
WITH SNOW PAN MELT

Size/ Exposure	r	Se (mm/day)	n
5S	0.99	2.3	6
5N	0.96	2.5	18
3S	0.98	2.4	6
3N	0.88	3.8	18
1S	0.97	2.2	16
1N	0.95	3.2	18
0	0.37	1.3	11
Combined	0.91	3.9	93

Partitioning of melt into energy budget components (Appendix 3, p. 69) showed that net radiation was the source

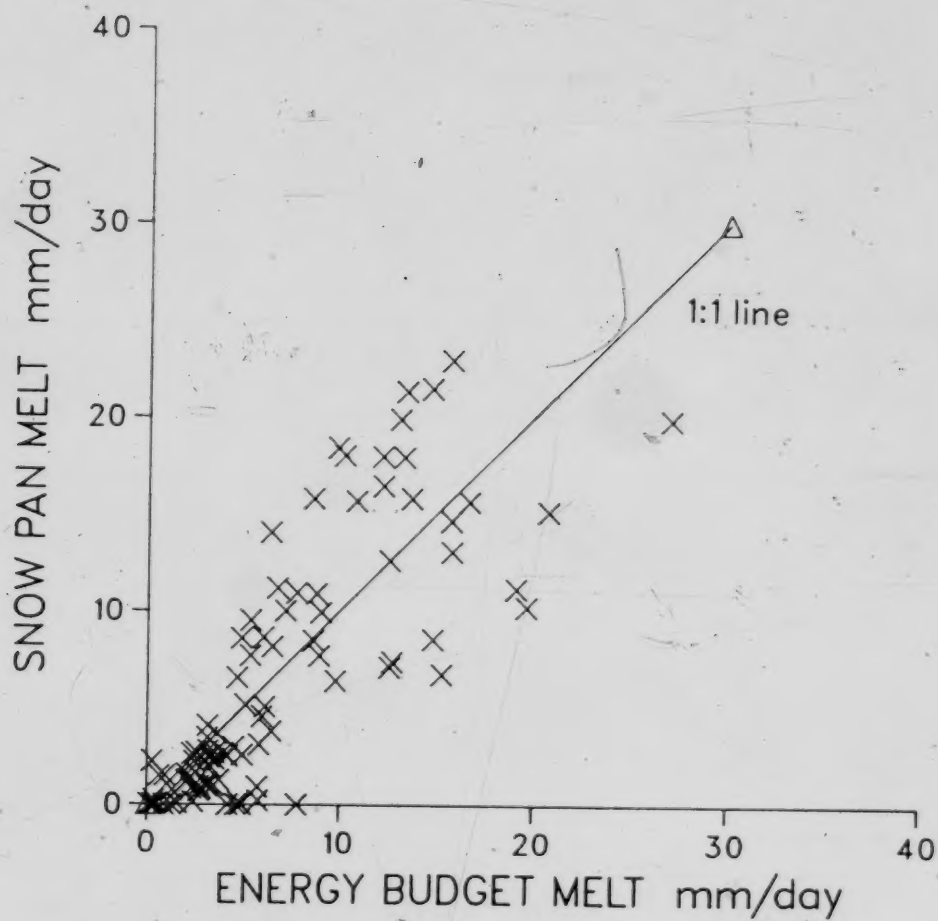


FIGURE 20. SNOW PAN MELT vs. ENERGY BUDGET MELT
(All sizes/exposures combined)

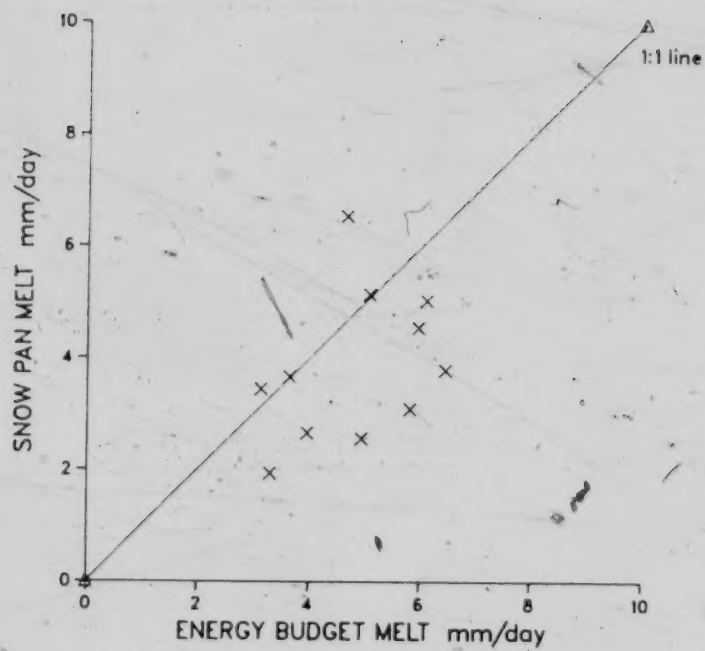


FIGURE 21. SNOW PAN MELT vs.
ENERGY BUDGET MELT (0)

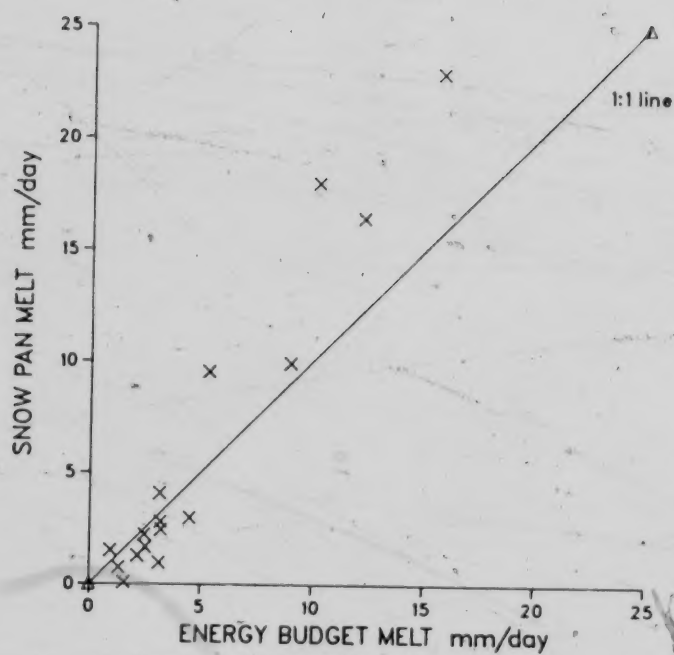


FIGURE 22. SNOW PAN MELT vs.
ENERGY BUDGET MELT (1S)

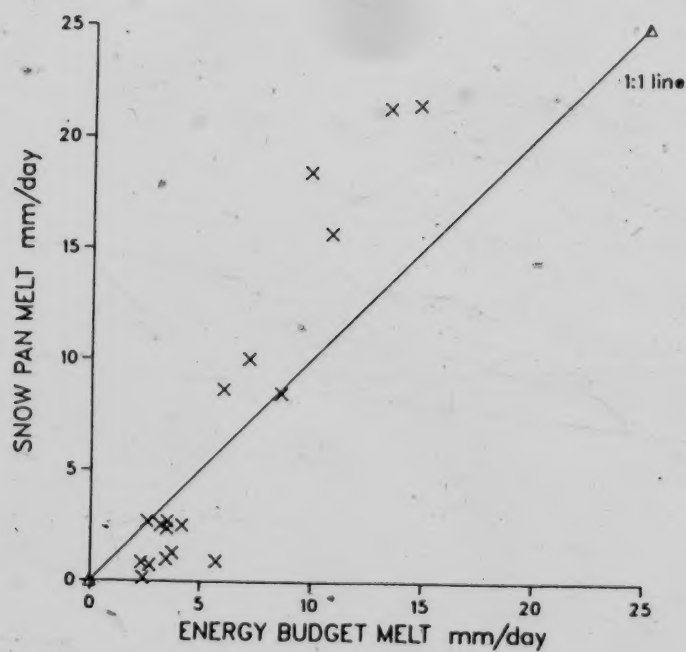


FIGURE 23. SNOW PAN MELT vs.
ENERGY BUDGET MELT (1N)

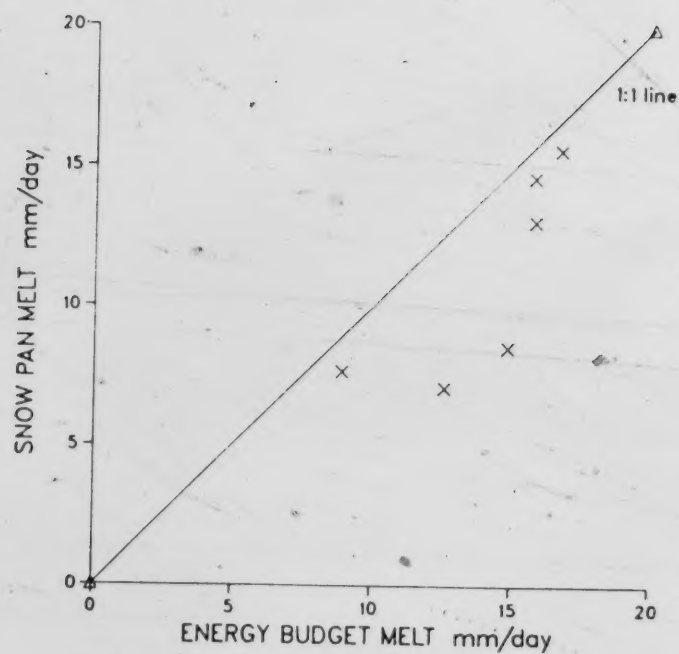


FIGURE 24. SNOW PAN MELT vs.
ENERGY BUDGET MELT (3S)

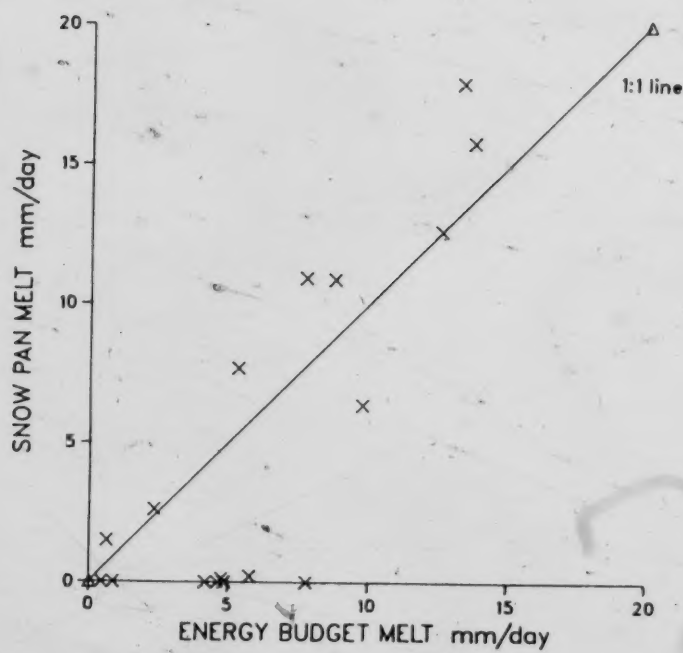


FIGURE 25. SNOW PAN MELT vs.
ENERGY BUDGET MELT (3N)

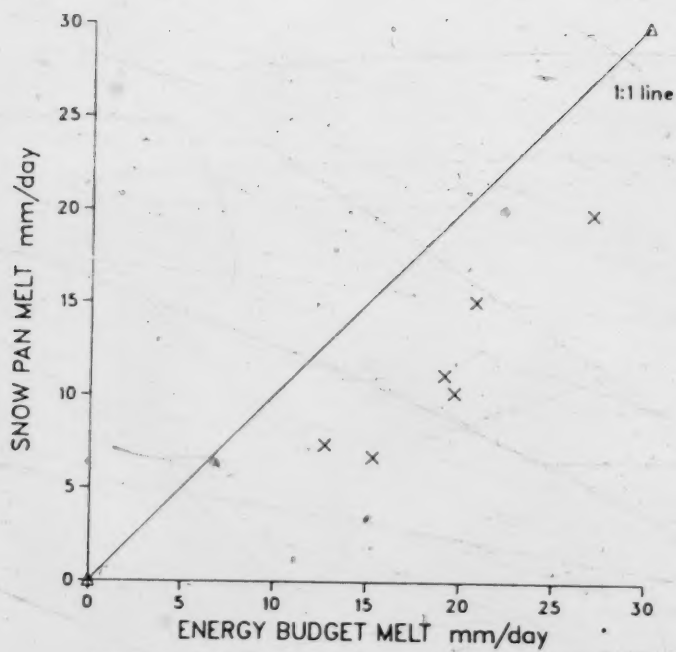


FIGURE 26. SNOW PAN MELT vs.
ENERGY BUDGET MELT (5S)

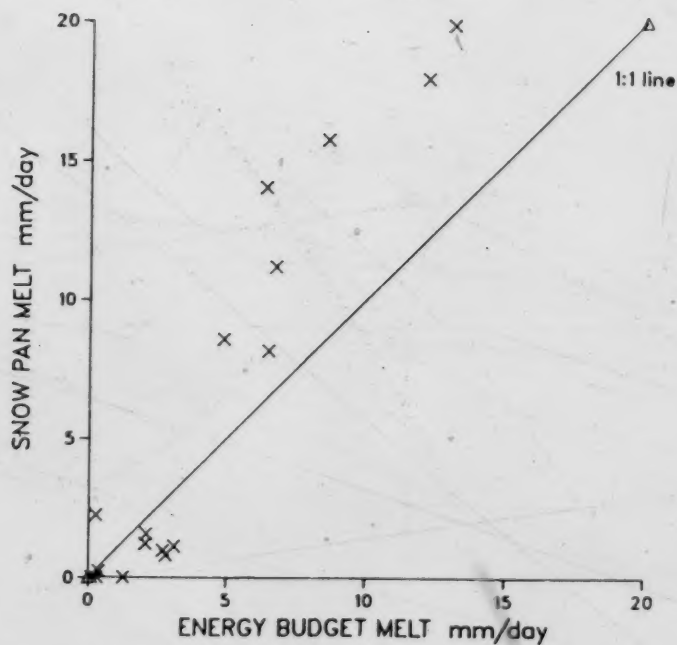


FIGURE 27. SNOW PAN MELT vs.
ENERGY BUDGET MELT (5N)

of at least 95% of the energy budget melt. The melt due to sensible heat, latent heat and advected heat accounted for the remainder, which was usually less than 2%. Net radiation varied from 1.2 ly/day to 217.6 ly/day (Appendix 4, p. 70), while sensible heat and latent heat were very small and varied from -1.9 ly/day to 3.2 ly/day.

These small values of sensible and latent heat were not the result of the assumed roughness length (Z_0) or the stall speed of the anemometers. The roughness length could have been increased or decreased by an order of magnitude and not have had any effect on energy budget partitioning. This was because of the influence of the stability reduction factor. The anemometers would require a stall speed of more than 1.0 m/s to change sensible or latent heat by 1 mm/day.

The importance of net radiation for melt is further supported by Table 6 (p. 47), which shows the results of the regression of pan measurements (melt and evaporation) against four meteorological parameters. The multiple r values for melt were all very high (0.96 to 0.99) except for OH (0.77). The parameter order indicates that for 5S, 5N, 3N and 1N, net radiation had the strongest correlation with melt. For 3S and 1S, it was second after wind speed and air temperature, respectively. This ordering of parameters was similar to that found by Zuzel and Cox (1975). Partial r values for the first two parameters varied from 0.78 to 0.98 for all size/exposures except OH, where the parameters had values of 0.69 and -0.39.

TABLE 6. REGRESSION OF DAILY SNOW PAN
MELT AND EVAPORATION

ON

METEOROLOGICAL PARAMETERS

SIZE/ EXPOSURE	MULTIPLE r	n	Se (mm)	PARAMETER ORDER (strong to weak partial r)
MELT				
5S	0.99	7	1.77	NR, WIND, RH, AT
5N	0.96	19	2.18	NR, AT, RH, WIND
3S	0.97	7	1.98	WIND, NR, RH, AT
3N	0.97	19	1.69	NR, AT, RH, WIND
1S	0.99	17	0.96	AT, NR, RH, WIND
1N	0.99	19	0.60	NR, AT, WIND, RH
0	0.77	12	1.11	AT, RH, NR, WIND
EVAP				
5S	0.96	7	0.53	AT, RH, NR, WIND
5N	0.46	19	0.67	NR, WIND, AT, RH
3S	0.99	7	0.17	RH, AT, NR, WIND
3N	0.79	19	0.78	NR, AT, RH, WIND
1S	0.48	17	0.47	AT, RH, NR, WIND
1N	0.72	19	0.79	NR, AT, RH, WIND
0	0.87	12	0.37	RH, NR, WIND, AT

NR = net radiation
 AT = air temperature
 RH = relative humidity
 WIND = wind speed

The multiple r values for evaporation were more variable, ranging from 0.46 to 0.99. Unlike melt, no single parameter exhibited a strong correlation for all, or even most, of the size/exposure combinations. Partial r values for the first two parameters ranged from -0.01 to -0.82.

Results for the regression of evaporation versus vapour pressure deficit are given in Table 7. Results showed no strong correlation between evaporation and vapour pressure deficit. Not only were the multiple r values quite low, but they were not consistently higher or lower for any specific regression.

TABLE 7. REGRESSION OF DAILY EVAPORATION
ON VAPOUR PRESSURE DEFICITS

Size/ Exposure	MULTIPLE r		
	VPD (0°C)	VPD (0°C, WIND)	VPD (SNOWT, WIND)
5S	0.37	0.58	0.67
5N	0.10	0.17	0.19
3S	0.46	0.61	0.50
3N	0.13	0.13	0.16
1S	0.00	0.01	0.02
1N	0.14	0.19	0.18
0	0.69	0.74	0.85

V. DISCUSSION

A. Timing of Ablation

Examination of daily ablation (Figures 8 and 9, p. 30) shows that for April 2 to 8 (the period for which snow was present on all size/exposure combinations) daily ablation was greater in the 0H, 3H and 5H openings than in the 1H opening. This difference in rates was due to the energy regimen of the openings, and in particular to the influence of net radiation. The 3H and 5H openings received an average of three to four times more net radiation than the 1H opening, while the uncut forest (0H) received twice as much as 1H. The cross-over in net radiation between 0H and the other size/exposures on April 14-16 was not the result of higher inputs of direct net radiation. A comparison of solar angle with opening geometry showed that the snow pans were in shadow.

The differences in ablation rates between north and south exposures was even more distinguishable than for the openings as a whole. Without exception, ablation rates were greater on south exposures than on north exposures (Figures 8 and 9, p. 30). This is especially evident from the melt graphs. Comparing these two graphs to those of the meteorological parameters (Figures 2 to 7, p. 25-27) gives a possible explanation. Air temperature and relative humidity did not vary greatly between exposures, nor between sizes. Wind speed and net radiation were just the opposite, varying

to a large degree between both exposures and sizes. Again, net radiation seemed to be the controlling factor. The trends exhibited by the net radiation graphs were almost identical to those of the melt graphs.

Evaporative contributions, on a daily basis, to ablation rates did not differ as noticeably between exposures as did melt. Indeed, the two graphs (Figures 12 and 13, p. 33) were remarkably similar.

Melt was the major source of ablation from the time measurements began (Figures 14 to 17, p. 34-36). It must be remembered, however, that the sampling period represented just the latter stages of the ablation season. Evaporation may have occurred earlier in the season when conditions did not allow melt to occur. These conditions include a snow temperature of less than 0°C and an air temperature less than the snow temperature. The greater the difference, the greater the vapour pressure gradient from the snow to the air. Satterlund (1972) states that given a snow temperature of -5°C , an air temperature of -10°C , a relative humidity of 60% and an average wind speed of 1 m/s, evaporation would be approximately 0.3 mm/day. The change-over to melt becoming the dominant ablation process is a reflection of the change in energy inputs, notably those associated with air temperatures greater than 0°C and high relative humidities, and their decreasing of the vapour pressure gradients.

Evaporation was consistently much less than melt (with a few exceptions) not only on a daily basis, but also in

terms of total amount (Figures 18 and 19, p. 37). The small amount of evaporation (usually less than 0.4 mm/day) was not surprising, in comparison to other studies. Evaporation was found to vary from 1.0 mm/day (measured) in 10H openings (Hutchison, 1966) to 10.4 mm/day (calculated) above tree line (Golding, 1978). It should be noted, though, that this range of values did not result from similar meteorological conditions (i.e. energy regimens), but rather from greatly differing conditions. Small forest openings would probably not experience as great a turbulent exchange of energy as the 10H openings or the open areas. Indeed, Golding's values were for conditions of strong, warm and dry chinook winds.

B. Apportioning of Ablation

The 3H and 5H openings had different proportions of melt and evaporation than did the 1H and 0H openings, with one exception. The main factor affecting melt and evaporation was exposure of the snowpack (ANOVA in Table 4, p. 39). The size of the opening was of less importance, probably because wind and net radiation were the only two parameters that varied greatly between exposures.

The large total melt from 1N is the exception mentioned previously. Instead of following the expected trend of being less than 1S, it was two percent greater. This anomaly might be the result of some form of edge effect, where the trees on the north exposure are having a greater radiative input into the snowpack due to their greater number (i.e. smaller

arc length) in the vicinity of the snow pans. In comparison to the north-south differences in the 3H and 5H openings, however, the difference in the 1H opening is not important.

The dependence of melt on net radiation is further supported by the regression results (Table 6, p. 47). The weaker correlation between melt and net radiation for 0H suggests that there were other factors of greater influence. However, the lower multiple r for the inclusion of all parameters suggests that it was not one of the four measured. The ranking of air temperature and RH could perhaps be an indication that sensible heat and latent heat transfer were the responsible factors.

Identifying the parameters which affected evaporation was not as straight-forward as with melt. There was no consistency in the regressions (Table 6, p. 47) to indicate which parameters it might be. It is known from meteorological theory that evaporation is influenced by the vapour pressure deficit (Lee, 1978). However, no such relationship was evident (Table 7, p. 48). Including wind (as a measure of turbulence) and using actual snow temperature 2-3 cm below the surface (instead of the assumed 0°C) did not improve the relationship. It should be noted, though, that evaporation takes place from the very top surface, so the snow temperature 2-3 cm deep may not be indicative of the surface temperature. In any case, the dominant parameters could not be identified.

C. Energy Budget Estimation

Energy budget melt did not agree closely with snow pan melt. The high r and low Se values (Table 5, p. 40) suggest, however, that the trends were similar and that the dominant factor of the budget may be the same as that of snow pan melt. With net radiation accounting for a minimum of 95% of the calculated budget melt, it may be inferred that net radiation was the major factor influencing snow pan melt.

The snow pan melt - energy budget melt graphs (Figures 22 to 27, p. 43-45) indicate that perhaps the contributions of sensible and latent heat to melt were not accurately determined. The large differences between pan and budget melt imply that energy transfer was not one-dimensional as assumed, but rather two-dimensional. Weisman (1977) concluded that sensible heat and latent heat had a strong effect of two-dimensional systems. The over-estimation of melt on 3S and 5S when air temperatures were low and net radiation was high suggests that more energy was lost to evaporation than was calculated. Similarly, the under-estimation of melt on 1S, 1N, 3N and 5N when air temperatures were high suggests that sensible heat was a greater source of energy than was calculated. These situations could result from air circulation caused by the rising of warmer air. On 3S and 5S, warmer air was replaced by cold, dry air. On 1S, 1N, 3N and 5N, it was replaced by slightly cooler air.

Price (1975) had sensible heat and latent heat accounting for almost 60% of daily melt when a strong flow of moist, warm air moved over the snow pack. These meteorological conditions were duplicated on April 17, except for the wind. On this day, sensible and latent heat averaged less than 1.0 ly. Examination of Equations 4, 5 and 6 (p. 16) shows the importance of wind in determining sensible and latent heat. Not only does a high value of U_a increase sensible and latent heat directly, but it also decreases the stability reduction factor.

The proportions of sensible and latent heat to net radiation measured in this study are comparable to those found by Granger et al. (1977), who concluded that sensible and latent heat were dependent, in part, on the movement of air masses.

The low r for OH is an indication that net radiation was less important in the uncut forest. The energy budget failed to indicate what was the important factor. The consistent over-estimation of the energy budget melt (Figure 21, p. 42) suggests that it may have been a combination of net radiation and latent heat. However, the Price and Dunne (1976) model was developed for a crown density less than 16%, and may not work for the uncut condition of 50% to 75% crown density. Indeed, Anderson (1976) concluded that energy budget models could not be used for forested situations because meteorological conditions were not variable enough.

D. Additional Considerations

The highest evaporation values were for days when precipitation occurred. One possible explanation for this is that on those particular days (April 18 and 20) the snow pans were over-catching compared to the rain gauge. The wind speed graph (Figure 7, p. 27) shows that for these days the average wind speed was less than 0.2 m/s. It was assumed, therefore, that the amount of precipitation collected by the rain gauge was indicative of the amount collected by the pans. Compared to the melt values (Figure 11, p. 32), the precipitation was negligible, and adjusting evaporation and melt by an additional 1 mm would not have much effect.

Thought was given to treating condensation as a precipitation input because it is an addition to melt. However, it was reasoned that condensation is a snowpack dependent process (i.e. dependent on low surface temperatures) and therefore is not a totally external input like precipitation. Also, the meteorological conditions responsible for condensation (e.g. high RH) could not be correlated to evaporation and melt if adjustments were made for condensation.

VI. CONCLUSIONS

A. Timing of Ablation

The four opening sizes experienced different ablation rates. Openings about 1H in diameter had rates two times lower than the uncut forest, and up to ten times lower than the larger openings. South exposures had rates up to 22 times greater than north exposures. Complete snow pack disappearance occurred first in 3S and 5S, and last in 1N, 3N and 5N.

B. Apportioning of Ablation

The apportioning of ablation between melt and evaporation did not change over the period of measurement. Melt was consistently greater than evaporation. It was theorized that evaporation would have constituted a larger proportion of ablation prior to this period, when snow surface temperatures were below 0°C and melt could not take place.

Meteorological conditions governed the relative contribution of the energy inputs (e.g. net radiation, sensible heat and latent heat) to ablation. For the period of measurement, net radiation was the major source of energy for melt. The source for evaporation could not be identified.

Total melt accounted for most of the total ablation. It ranged from 70% (0) to 97% (5S). The openings and exposures

had substantial increases in melt compared to the uncut (OH) forest (Table 3, p. 38). With this increase in melt (and corresponding decrease in evaporation), the potential for yield management is obvious.

C. Energy Budget Estimation

The energy budget estimates of melt were not in close agreement with snow pan estimates. The budget consistently over or under-estimated melt. The horizontal transfer of sensible and latent heat may have been of greater importance than the vertical transfer. The r values of the comparison with snow pan melt averaged 0.87 and ranged from 0.37 to 0.99, with Se ranging from 1.3 to 3.8 mm/day, indicating that the budget and pan estimates were of similar magnitude.

D. Questions

A purpose of research is not only to attempt to answer questions, but also to generate new ones, which can then be used as indicators for future research. This study was no exception and several questions arose.

How significant is the edge effect upon ablation processes, especially in small openings? Does it extend a relative or an absolute distance into the openings? Of what effect is the arc length of circular openings? Answers to these questions may have a bearing on the choice of opening size to meet specific management goals.

What is the timing of the ablation processes during the day? When are the most productive times for melt? How are these times related to meteorological conditions? Some studies have already attempted to address this question (Price, 1975), but no consistent results have been found. If melt and evaporation were measured continuously, perhaps by some form of lysimeter, then better correlations to meteorological parameters may be achieved. This is especially true for evaporation.

Are snow pack thermodynamics constant, given constant meteorological conditions? Or is there a sort of snowball effect as the melt season progresses, with melt producing even more melt? The internal heat and structural conditions of a snow pack are interdependent, so affecting one may affect the other.

Are melt and evaporation dependent on the depth of the snow pack? A deep snow cover would take a longer time and more energy to become isothermal at 0°C , the condition necessary to allow melt to exit the pack. Until that point is reached, melt would undergo a freeze/thaw cycle and thereby alter the snowpack heat and structural conditions.

E. Concluding Remarks

This study has shown that the size of canopy openings can affect ablation processes through changes in the energy regimen. From a watershed management perspective, two possible alternatives can be examined:

1) If an increase in water yield is the goal, then a 3H opening is the optimum size. Not only does it accumulate more snow than the other sizes (Golding and Swanson, 1978), but a greater proportion of its ablation is melt.

2) If altering flow regimen by delaying melt is the goal, then a 1H opening is the optimum size. It takes longer for melt to become the dominant ablation process.

The potential for other management schemes (e.g. strip cuts with only one exposure to increase/delay melt) and applications (e.g. to silviculture), through energy regimen manipulation, is limited only by the imagination of the manager.

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Appendices

APPENDIX 1. CALCULATION OF EVAPORATION, MELT
AND ABLATION FROM SNOW PAN DATA

At t_0 ,

$$W_0 = S_0 + M_0 + E_0$$

where W = total mass
 S = mass of snow
 M = mass of melt
 E = mass of evaporation

$$M_0 = E_0 = 0$$

$$W_0 = S_0$$

At t_1 ,

$$W_1 = S_1 + M_1$$

$$W_2 = S_1$$

$$W_0 = S_1 + M_1 + E_1$$

Therefore,

$$\begin{aligned} \text{Evaporation} &= W_0 - W_1 \\ &= (S_1 + M_1 + E_1) - (S_1 + M_1) \\ &= E_1 \end{aligned}$$

$$\begin{aligned} \text{Melt} &= W_1 - W_2 \\ &= (S_1 + M_1) - S_1 \\ &= M_1 \end{aligned}$$

$$\begin{aligned} \text{Ablation} &= W_0 - W_2 \\ &= (S_1 + M_1 + E_1) - S_1 \\ &= M_1 + E_1 \end{aligned}$$

APPENDIX 2. MAXIMUM AND MINIMUM VALUES OF
DAILY METEOROLOGICAL PARAMETERS

SIZE/ EXPOSURE	AIR TEMPERATURE (°C)		RELATIVE HUMIDITY (%)		WIND SPEED (m/s)		NET RADIATION (ly/min)	
	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN
5S	12.1	-6.7	103	21	1.4	0	0.69	-0.063
5N	23.8	-7.5	105	17	1.7	0	0.37	-0.060
3S	12.3	-6.1	102	21	1.0	0	0.54	-0.061
3N	21.7	-7.4	105	23	0.9	0	0.62	-0.070
1S	24.1	-6.4	102	17	0.6	0	0.33	-0.024
1N	23.9	-6.1	103	17	0.6	0	0.32	-0.024
0	10.1	-5.6	99	22	0.4	0	0.30	-0.033

APPENDIX 3. MAXIMUM, MINIMUM AND (MEAN) VALUES OF
ENERGY BUDGET COMPONENTS AS PERCENTAGES
OF DAILY ENERGY BUDGET MELT

SIZE/ EXPOSURE	Qn		Qh		Qe		Qv	
	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN
5S	100.6 (100.1)	99.8	0.4 (0.1)	0.0	0.0 (-0.3)	-0.9	0.2 (0.0)	0.0
5N	104.5 (98.6)	95.3	9.1 (2.0)	0.0	0.0 (-1.4)	-8.9	5.1 (0.8)	0.0
3S	100.4 (100.1)	99.8	0.2 (0.1)	0.0	0.0 (-0.2)	-0.6	0.2 (0.1)	0.0
3N	100.1 (101.2)	97.3	1.3 (0.2)	0.0	0.0 (-1.6)	-0.5	2.7 (0.3)	0.0
1S	100.1 (99.7)	96.9	0.1 (0.0)	0.0	0.0 (0.0)	-0.3	3.1 (0.3)	0.0
1N	103.2 (99.8)	97.3	0.1 (0.0)	0.0	0.0 (-0.2)	-0.2	2.7 (0.4)	0.0
0	100.0 (99.9)	99.3	0.0 (0.0)	0.0	0.0 (0.0)	-0.1	0.7 (0.1)	0.0

APPENDIX 4. MAXIMUM, MINIMUM AND (MEAN) VALUES
OF ENERGY BUDGET COMPONENTS (ly/day)

SIZE/ EXPOSURE	Qn		Qh		Qe		Qv	
	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN
5S	217.6 (153.2)	101.7	0.8 (0.3)	0.0	0.0 (-0.6)	-1.9	0.2 (0.1)	0.0
5N	103.4 (32.0)	1.2	3.2 (0.3)	0.0	0.0 (-1.0)	-1.5	1.4 (0.2)	0.0
3S	134.1 (112.9)	71.1	0.3 (0.1)	0.0	0.0 (-0.2)	-0.9	0.2 (0.0)	0.0
3N	108.6 (49.8)	3.6	0.5 (0.1)	0.0	0.0 (-0.1)	-1.4	1.4 (0.2)	0.0
1S	126.0 (40.2)	7.5	0.0 (0.0)	0.0	0.0 (0.0)	0.0	1.3 (0.1)	0.0
1N	117.8 (47.8)	19.2	0.0 (0.0)	0.0	0.0 (0.0)	-0.6	1.5 (0.2)	0.0
0	51.6 (38.5)	24.9	0.0 (0.0)	0.0	0.0 (0.0)	0.0	0.2 (0.0)	0.0